The effect of wet-pressing on paper quality

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Content

Summary

The wet-pressing section of a paper machine has a significant influence on both energy efficiency and quality of the final product. During wet pressing a pressure is applied to the paper which compacts the wet web causing both increased dry content and increased web density. The higher the dry content after wet-pressing the higher the energy efficiency of the overall production process. The effect of the increased density may be positive or negative depending on the grade under production.

Due to the strong interaction between the press section and paper properties, measures can not be taken in the press section without affecting the properties of the final product. The current wet-pressing models are strictly dewatering models and therefore do not provide the required information to allow for optimisation of the total wet-pressing performance.

The question at the start of the study was: "What is the additional information required to allow for both a reliable prognosis of dewatering rates and of paper properties, and how can these aspects be modelled?".

We found that calculation of the density after wet-pressing is the first requirement of a model that has to give information on paper quality. Therefore the aim was focussed on understanding of the observation that an extended nip press (ENP) or shoe nip press yields for some furnishes a lower density than a roll nip press at equal outgoing moisture ratio. Based on this we developed the hypothesis that fibre dewatering is the key to understanding this phenomenon.

Since the current dewatering theory did not incorporate fibre dewatering explicitly, this resulted in the development of a double continuous macroscopic model describing flow and compaction of a compressible porous medium consisting of compressible porous particles. In other words: compaction and dewatering of the fibres is calculated separately from the compaction and dewatering of the network formed by the fibres.

The flow through the inter-fibre pores (pores located in between the fibres) and the flow from and into the intra-fibre pores (pores inside the fibre wall) are described by equations derived from the Kozeny-Carman equation. In this way the retarding effects of dewatering on compaction can be calculated separately from the viscous effects related to the compaction of the fibres and/or the network.

The mechanical model was based on the assumption that the mechanical behaviour of the wet web is the sum of the behaviour of the fibres and the network. The description of the mechanical behaviour of the fibres and the network was based on experimental work presented in this thesis, additionally we used work previously published by third parties.

These equations together form a new press performance theory allowing for the simultaneous calculation of the dewatering and the compaction of the web at every location in the nip.

This press performance theory states that the driving force for fibre dewatering is, at constant press impulse, lower in an ENP than in a roll nip press. This has some far reaching consequences. Firstly, during wet pressing more water may remain inside the intra-fibre pores in an ENP than in a roll nip press. This is a revolutionary insight, since until now fibre dewatering was assumed to occur more in an ENP due to the longer nip residence time. Secondly, the paper web with the highest degree of fibre dewatering has the lowest density after wet-pressing according to the press performance theory. This explains the difference in density that under some circumstances may occur between a roll nip press and an ENP. This makes the press performance theory presented in this thesis the first press performance theory explaining the density difference.

Nevertheless some future work is required before this model may be applied in industry. First of all the press performance theory needs to be validated. This will require significant dynamic material testing.

- To test the hypothesis that fibre dewatering is less in an ENP than in a roll nip press, if the roll nip press yields higher density furnishes.
- To determine the model parameters to allow for more detailed calculations using a numerical version of the presented analytical model.

After that implementation projects maybe started.

Samenvatting

De perspartij van een papiermachine heeft een significante invloed op zowel de energie efficiency als de kwaliteit van het eindproduct. Dit komt doordat in de perspartij de natte papierbaan samengedrukt wordt, waardoor enerzijds de papierbaan ontwatert en anderzijds de dichtheid van de papierbaan blijvend verhoogd wordt. Hoe meer de papierbaan in de perspartij ontwatert, hoe hoger de energie efficiency van het totale productie proces is. Het effect van de verhoogde dichtheid kan per saldo positief of negatief uitvallen voor de papierkwaliteit, afhankelijk van het type papier dat geproduceerd wordt.

Door de sterke verwevenheid van de perssectie en papiereigenschappen hebben veranderingen in de perssectie direct effect op de eigenschappen van het eindproduct. Helaas zijn de huidige modellen van de perspartij pure ontwatermodellen en leveren daarom niet de benodigde informatie die de totale optimalisatie van de perspartij (ontwater efficiëntie en optimalisatie van het effect op de papiereigenschappen) mogelijk maakt.

Aan het begin van het onderzoek hadden we daarom een vrij algemene vraagstelling: "Welke informatie is er nodig om een goede inschatting te kunnen maken van zowel de ontwatersnelheid in de perspartij als het effect van de perspartij op de papiereigenschappen en hoe kunnen deze aspecten gemodelleerd worden?".

Dit leidde tot de conclusie dat het kunnen berekenen van de dichtheid van het natte papier direct na verlaten van de perspartij een eerste vereiste is om het effect op alle papiereigenschappen in te kunnen schatten. Daarom is het doel beperkt tot het begrijpen van het verschil in effect op de dichtheid dat voor sommige papieren optreedt tussen een schoennip pers en een rolnip pers bij gelijk uitgaand drogestofgehalte. Op basis van deze observatie is de hypothese ontwikkeld dat vezelontwatering de sleutel is tot het begrijpen van dit verschil.

Aangezien de huidige ontwater theorie geen expliciete rol voor vezelontwatering erkent heeft dit geresulteerd in de ontwikkeling van een dubbel continue macroscopisch model voor de beschrijving van een samendrukbaar poreus medium opgebouwd uit samendrukbare poreuze deeltjes. In andere woorden: samendrukking en ontwatering van vezels wordt apart berekend van de samendrukking en ontwatering van het netwerk dat door de vezels gevormd wordt.

De stroming van water in en uit de vezels en de ruimtes tussen de vezels wordt beschreven op basis van de Kozeny Carman vergelijking. Aparte vergelijkingen worden gebruikt voor de stroming tussen de vezels (door de inter-vezel poriën) en de stroming in en uit de vezel (van en naar de intra-vezel poriën). Hierdoor zijn vertragende effecten die het water kan hebben op de samendrukking apart gehouden van viskeuze eigenschappen van de vezels en het netwerk.

Het mechanische gedrag van de papierbaan is beschreven als de som van het gedrag van de vezels en het netwerk. De beschrijving van het mechanische gedrag van de vezels en het netwerk is bepaald op basis van experimenteel werk dat in dit proefschrift gepresenteerd wordt, gecombineerd met bevindingen gerapporteerd door derden.

De bovengenoemde vergelijkingen vormen samen een nieuwe pers-performance theorie waarmee simultaan de ontwatering en de verdichting van de papierbaan op ieder moment in de nip berekend kan worden.

Volgens deze pers-performance theorie is in principe de drijvende kracht voor vezelontwatering lager in een schoennip pers dan in een rolnip pers. Dit heeft verstrekkende gevolgen. Ten eerste kan dit tot onder bepaalde omstandigheden tot een andere verdeling van het water over het blad leiden waardoor er meer water in de vezel (in de intra-vezel poriën) achter blijft als de papierbaan in een schoennip pers ontwaterd wordt dan in een rolnip pers. Dit is een revolutionair inzicht aangezien tot nog toe werd aangenomen dat vezelontwatering meer zou optreden in de schoennip pers door de langere nip verblijftijd. Ten tweede heeft (volgens de pers-performance theorie) de papierbaan met minder vezelontwatering een lagere dichtheid. Dit verklaart het verschil in dichtheid dat onder bepaalde omstandigheden op kan treden tussen rolnip en schoennip persen. Hiermee is deze nieuwe pers performance theorie de eerste pers theorie die dit verschil verklaart.

Niettemin moet er nog heel wat werk verzet worden voordat dit model toegepast kan worden in de industrie. Als eerste moet het model gevalideerd worden. Hiervoor zijn uitgebreide dynamische persproeven nodig.

- Voor het testen van de hypothese dat de hoeveelheid water in de vezels hoger is in een schoennip pers dan in een rolnip pers; onder voorwaarde dat de dichtheid van het papier uit de schoennip pers lager is bij gelijkblijvend uitgaand drogestofgehalte.
- Voor het bepalen van de model parameters die nodig zijn om nauwkeurige berekeningen te kunnen maken.

1 Introduction

1.1 Background

This thesis is the result of the coalescence of the long-term goals of the Dutch government and the Dutch paper and board industries at the end of the 20th century. Over the last years the following trends could be observed that still seem to continue today:

- Additional requirements regarding the paper quality caused by the increasing importance of the appearance of products and a wide spread use of new printing techniques such as laser and colour printing (Bublinski et al. 2002; Danby 1998; Farell et al. 2002; Oittinen and Saarelma 1998; Ravary 1999; VOITH 2002).
- Decreasing quality of base material because of the continuous search for cost reduction and increasing recycle rates.
- Increasing energy prices, making high dry contents before the drying section desirable, whereas fear for quality decrease due to increased wet-pressing prevents papermakers from increasing the outgoing dry content after wet-pressing .

For the above reasons the Dutch paper and board industries have been looking for ways to increase profit by decreasing costs, for example by increasing energy efficiency and increasing revenues by increasing product quality. Therefore, the Dutch paper and board producing industry was interested to learn more about the influence of wet-pressing on final paper quality. Currently, this information is available only for a given machine, stock, and product combination.

At the same time the Dutch government, bound by the Kyoto treaty, was looking for ways to reduce the emission of greenhouse gasses. The paper and board industry, being an energy intensive industry, raised the government's concern.

In the eighties the Dutch research organisation TNO carried out several reports on energy saving potential of the Dutch paper and board mills, among others a huge energy saving potential was identified in the wet-pressing section i.e. a cost reduction for the industry. By 1999 a considerable energy efficiency increase was realised, but the alleged potential for increase of energy-efficiency in the press section was not realised. Fear of quality loss prevented papermakers from implementing the suggestions made in the TNO report. Due to the strong interaction between the press section and paper properties, measures can not be taken in the press section without

affecting the properties of the final product. The current wet-pressing models are strictly dewatering models and therefore do not provide the required information to allow for optimisation of the total wet-pressing performance.

The question is what is the additional information required to allow for both a reliable prognosis of dewatering rates and of paper properties, and how can this be modelled?

1.2 Aim

The starting point of this thesis work was the wet-pressing model developed at TNO by Riepen, Mulder and Sinon, which was (and still is) a state of the art dewatering model that had proven it's validity in difficult applications such as predicting the moisture and temperature distribution in a wet sheet during Condebelt or Impulse Drying (Riepen 2000).

At first the aim of this thesis was to provide the TNO dewatering model with a more scientific base by replacing the empirical relations by general applicable engineering relations.

Therefore we explored the field by verifying a number of publications using simple experimental techniques. Evaluation of the experimental results raised the insight that the current dewater theory was insufficient to incorporate the effect of wet-pressing on paper quality in any dewatering model. Therefore the aim was focussed on understanding of the observation that an extended nip press (ENP) or shoe press yields for some furnishes a lower density than a roll nip press at equal outgoing moisture ratio. Based on this we developed the hypothesis that fibre dewatering is the key to understanding this phenomenon. Therefore we focussed from then on the development of a double continuous model allowing for the explicit calculation of the rate of fibre dewatering, including a new mechanical model of the wet web differentiating between the deformation of the network and the fibres.

1.3 Outline

A short introduction to pulp production and paper making is given in *chapter 2*. In addition a description is given of the different size scales at which wet-pressing can be studied.

Chapter 3 looks at the scale effects related to the difference in scale between the pore radii and the sheet thickness. Assumptions that have to be made to apply macro-scale equations to the flow in the pores, i.e. to micro-scale processes, are verified. The understanding of this theory is of crucial importance to the interpretation of experimental data.

Wet-pressing compacts paper. *Chapter 4* gives an overview of the present understanding of which wet-pressing variables determine the effect of the wet-pressing on the final degree of compaction of the dried sheet. Some experimental results are presented, these show that the outgoing moisture ratio strongly influences the way wet-pressing affects the final density of the sheet, in addition it shows the effect of wet-pressing on other properties than the density. This chapter also describes our experimental equipment in detail.

Chapter 5 is dedicated to rewet theory. The Differentiated Permeability Surface Layer (DPSL) rewet theory suggested in 2000 (I'Anson and Ashworth 2000) is put to the test.

Fibre dewatering occurs under certain conditions during wet-pressing. *Chapter 6* presents a method for determining the part of the fibre dewatering potential as a function of the applied pressure.

Chapter 7 presents experimental results that show the effect of wet-pressing on the inter-fibre pore radius. This is relevant to wet-pressing performance since the pore size distribution has a significant effect on the permeability of the furnish to water.

Chapter 8 describes the deformation stresses that may occur in a wet web during compaction. An attempt is made to bring the description of these deformation stresses in line with common deformation physics

In *chapter 9* the results of the different chapters are used to improve the insights obtained by the existing wet-pressing models. Using this new insight a new approach is suggested to evaluate the difference between roll nip presses and so-called shoe nip or extended nip presses on the paper properties.

1.4 Vocabulary

In this work some words have a specific meaning, that may differ from normal English usage. Below is a short dictionary of words the specific meaning of which may not be immediately clear from the context:

Paper	Material made of fibrous vegetable material deposited from an aqueous suspension. In this thesis paper is used as a general term for the finalised product independent of base weight, i.e. including board.
Board	Paper of a high base weight, normally > 170 g/m^2.
Web	During the production process of paper, a continuous web is formed in the sieve section at the start of the paper machine. In the subsequent process steps this web is dewatered and the surface of the web is prepared for specific applications. The web remains unbroken and is wound on the winder at the end of the paper machine. Therefore, we use the word web to indicate the paper while it is being produced on the machine.
Hand sheet	A piece of paper made on a laboratory sheet former, i.e. instead of a continuous web a single sheet is formed. Hand sheets are used to study on a laboratory scale, i.e. before pilot tests, the effect of changes to the pulping process and/or the paper machine on the final paper quality.
Sample	Piece of web or hand sheet before it is dried, as used in the wet-pressing tests described in this thesis.
Furnish	Reference to the composition of the paper. For example the sentence: "We used different furnishes", means that we used samples differing in the type of pulp.
Freeness	The freeness of a pulp is an indication of it's dewaterability. Two methods exist to measure freeness: the Schopper-Riegler test, with the result expressed in SR units, and the Canadian Standard Freeness test, with the result expressed in CSF units.
Machine width	Width of the paper machine, also referred to as cross direction (CD).
Machine direction	Machine direction (MD) is the direction parallel to the length of the paper machine. In most fast producing paper machines

	the fibres are aligned parallel to this direction.
Nip	Contact area between paper, roll and felt(s), location in the press where pressure is applied to the paper.
Nip length	The nip covers an area. The dimension in MD is called the nip length and the dimension parallel to the CD is called the machine width.
Line pressure	The pressure at mid-nip if the nip was the line of contact between the two rolls forming the nip, i.e. load applied to the axes of the rolls divided by the machine width. In practice the line of contact widens to a contact area, providing the nip with a length and a width.
Press impulse	The pressure applied in the nip integrated over the time during which the pressure was applied. According to conventional dewatering theory the degree of dewatering of a certain furnish remains constant if the press impulse remains constant. The press impulse can be calculated as the ratio of the line pressure over the machine speed.
Strain	Distortion of a material by forces acting on it. The strain is the ratio of the deflection to the dimension of the material before distortion and is therefore without unit.
Stress	The (reaction) forces per unit area within a material tending to change the material's dimensions. Stresses are the result of forces acting on a material.
Hydraulic pressure	The pressure exerted by water on it's surroundings. Hydraulic pressure decreases to zero when the forces acting on the water decrease to zero, i.e. when the flow resistance met by the water decreases to zero or when the applied load is removed.
Structural pressure	Part of the stress in the material that causes the net deformation of the material.

1.5 References

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VOITH "Science Dialog PROcess & PROgress." *International Customer Conference.*

2 The paper production process at a glance

Although the focus of this thesis is on wet-pressing, the different parts of the production process are related in such a way that some background information on the whole process is necessary to understand the experimental approach. In the following an attempt is made to provide this background information. This information is by no means complete and interested readers are referred to the Fapet Oy series, Paper-making Science and Technology, or other handbooks on paper-making technology.

In this chapter the different stages of the paper-making process are described, from the fibre source, the pulping method and the paper machine to the paper characteristics of the final sheet. The characterisation of the paper-making process on the paper machine occurs at different size scales:

- Paper machine 0.2 - 200 meter scale
- Nip dimensions 0.05 mm - 1 meter scale
- Pores 0.01 - 50 micron scale

In the next chapter we will focus on how these different scales are related.

2.1 Fibre sources and pulping methods

Paper and board is made of fibres. Fibres are made of different types of polymers: cellulose, hemicellulose, lignin and natural resins. The cellulose and hemicellulose form twines. The twines form a layer. The layers are covered with lignin and resins, giving strength and stiffness. Several layers together form the fibre, cf. figure 2-1. When twines of (hemi)cellulose are partially freed from the fibre structure they are called fibrils. Fibrils are very important to fibre bonding.

The characteristics of these fibres have a significant influence on the properties of the final product. The properties of the fibres are determined by the fibre source and pulping method.

The most used fibre sources are wood and recycled paper. The first source yields so-called virgin fibres and the second source recycle fibres. The process of releasing fibres from the wood or paper is called pulping. The pulping method depends on the fibre source.

When recycling paper, fibres are released by dispersing the paper in water. The pulping method consists of dispersing the collected paper after which the dispersed fibres are purified from ink and dirt using cyclones and screens, and refined to get sufficient active fibre surface.

Contrary to fibres in paper, fibres in wood are held together by chemical bonds in a matrix structure. Lignin molecules, i.e. a type of three dimensional polymer and resins, act as glue. Therefore, virgin fibres are not so easily released as secondary fibres. Basically, two approaches exist to pulp wood: mechanical and chemical. These methods differ mainly in the extend to which the lignin and resins are removed and the degree to which the other polymers are affected.

In mechanical pulping the fibres are torn apart form the wood by pressing the wood against a fast rotating grinder. The yield[1] of this pulping process is high (95-99%). The pulp obtained by this method is characterised by:

- Damaged fibres
- High fines (small fibre parts) content
- High degree of fibrillation (strings of cellulose molecules partly freed from the fibre wall)
- High percentage of fibres with a thick and stiff fibre wall.
- High lignin content

Therefore, paper made using mechanical pulps has a low density combined with a high stiffness, but at a low strength. Additionally, these papers yellow rapidly.

In chemical pulping the wood is cooked under high pressure in a very acid or a very alkaline solution. The yield of this method is about 50 to 60%. The pulp obtained by this method is characterised by:

- No fibre damage after the alkaline sulphate process. After the acid sulphite process the cellulose chains may be damaged
- Long flexible fibres with a relatively thin fibre wall.
- Low lignin content and reduced hemicellulose content.
- Low degree of fibrillation. To obtain sufficient fibrils these pulps are often refined after pulping.

Therefore, papers made of chemical pulps have a high surface smoothness, a high strength, and a low bulk. After bleaching they posses a high level of whiteness and a low tendency for yellowing. Paper made of sulphate pulps offers particularly high strength, while sulphite pulps may yield the highest whiteness.

| [1] Yield - Production of pulp fibres expressed as a mass percentage of the wood supplied to the process.

The sulphate process is the most widely applied chemical pulping process (Korpeinen and Ainamo 2003). This is an alkaline process, during which a pH of 12 can be reached at temperatures of 160-180 °C and pressures of 1-6 MPa. Pulp resulting from this process is called kraft pulp[2]. Due to the chemical reactions occurring during kraft pulping, the pulp may darken, so bleaching is necessary for all printing grades.

Thermo-mechanical pulp (TMP) currently is the most widely used mechanical pulp. It is called thermo-mechanical pulp since the pulp is heated with steam before being torn apart in a refiner. As a result of the applied heat the fibres are more easily freed from the wood matrix, reducing fibre damage and coarse fibre content.

To improve whiteness, mechanical pulp may also be bleached.

Apart from the pulping method, the fibre source also has a significant effect on fibre properties. Wood from deciduous trees, also known as hard wood, generally yields coarser and shorter fibres than those obtained form conifers (soft wood). Additionally, large differences exist between different types of hardwood and softwood, or even between samples of a single type of timber grown under different circumstances.

The properties of recycled fibres vary greatly according to the source. The three main categories are: Mill Broke, Post Industrial Waste (PIW) and, Post Consumer Waste (PCW).

- Mill broke is reused paper that was produced off specification. This may be paper from any stage in the production process, from the wet web directly off the wire to finalised paper that has been incorrectly cut.
- PIW consists of paper collected from offices or printing shops. This is well-sorted paper, normally made of virgin fibres. Consequently, fibres obtained from PIW will be more similar to virgin fibres.
- PCW is paper collected from households. PCW normally consists of a mixture of paper and board, with varying percentages of recycled paper.

Each time fibres are reused, the fibre wall degrades a little further, until it is completely worn down. Degradation of the fibre walls of mechanically pulped fibres may change the properties of these fibres to more closely resemble chemically pulped fibres. Further recycling will inevitably results in loss of fibre quality.

| [2] Kraft is German for strength. The German developer Dahl called his invention the kraft process in reference to the high fibre strength.

2.2 Paper machine

After fibres have been pulped the pulp is diluted to a highly aqueous mixture of 1-2% fibres by mass. Additives are added, and the pulp is sent to the paper machine. The function of the paper machine is to separate fibres and water in such a way that a sheet with the required properties is formed. This is achieved in three steps. First the forming section, followed by the press section and the dryer section, cf. figure 2-2. More modern versions of the forming section and the press section are shown in figure 2-3 and figure 2-4 respectively.

Depending on the type of paper machine, machine speed varies between 25 and 2000 m/min, i.e. 0.4 and 33 m/s, while paper machine widths vary from 2 to 12 meters.

2.2.1 Formation:

The aqueous solution is spread over a wire, and drained by gravity and suction. The aim of the formation process is to form a web with an even fibre distribution and to remove 90-95% of the water. After formation the web's dry content is 20-30%. This is enough to give the wet web sufficient strength to support it's own weight. The oldest formation device is the Fourdrinier table shown in figure 2-2. The draw-back of this method is that a density gradient may occur over the thickness of the sheet. Modern machines dewater almost instantly between two wires, allowing for faster dewatering and a more symmetrical sheet structure, cf. figure 2-3.

2.2.2 Wet-pressing

During formation the pulp forms a wet capable of supporting it's own weight. However, since the wet web is very sensitive to stretching in the machine direction, the web is supported as much as possible while moving through the wet-pressing section. Conventionally, the wet web is forced to dewater by leading it through several nips. A nip is the contact area between two rolls pressed together, cf. figure 2-5. In this configuration the aperture of the nip is variable and the load is a setting parameter. The load is applied to the shafts of the rolls, as a results of which the rolls tend to bend slightly in the middle. The crowning of the rolls is adapted to keep the applied pressure profile even over the cross-direction (direction parallel to the machine width).

Together with the web a felt moves through the nip. This felt serves a double function: it supports the web between two consecutive nips, and inside the nip it provides an

escape route to the water forced from the web. To prevent slipping between the web and a felt, felts move through the nip(s) at the same speed as the web.

The felt's name derives from the fact that it used to be made of felt[3]. Nowadays it is usually made of polymers, mainly nylon, and consists of a combination of non-woven fabrics needled on top of a woven substrate.

In addition to the roll nip described above, extended nip presses (ENP) or shoe nip presses are in use. The advantage of these nips is that they have an extended nip residence time, resulting in improved dewatering without increasing the pressure. This extended nip residence time is realised by replacing one of the rolls by a load shoe, providing a comb-shaped contact surface to the mating roll. Since the load shoe is static, a belt moves over the load shoe at the same speed as the felt to decrease felt attrition cf. figure 2-6. Figure 2-4 shows an example of a modern press section consisting of a combination of ENPs.

Pressures applied in the nip vary between 1.0 and 12 MPa. The pressure increases with increasing dry content of the paper. The temperature varies between 25 and 75 ^{o}C (Dahl 1989). The pressure applied depends on the type of paper being produced, the nip length, and the dry content of the web when entering the nip. The nip length varies between 10 and 25 mm for a roll nip press, and between 100 and 250 mm for an ENP or a shoe nip press. The press roll diameters normally vary between 400 and 900 mm.

2.2.3 Drying

After wet-pressing the dry content of the wet web varies between 35 and 55%, depending on the type of paper/board being produced. The remaining water has to be removed by means of evaporation. To supply the required heat to the wet web, it is leaded over a sequence of steam-heated drums, commonly referred to as drying cans. To ensure good contact between the cans and the steaming hot web, drying wires tighten the web to the cans. Drying by evaporation is an energy-intensive process.

2.2.4 Finishing

The procedures described above form the basis of paper-making. To optimise the web's surface properties for printing purposes, some additional processes may be applied such as sizing, coating, and calendering. These process steps are important to

[3] Felt is a material made by pressing together wet layers of wool.

the final appearance and properties of the paper. They improve the surface structure and variations in the base paper may be corrected to some extend. However, the success of these finishing steps depends heavily on the quality of the base paper. Proper process control on formation and wet-pressing therefore remain key to producing top quality paper and board. Therefore, the scope of this paper is limited to the wet-pressing section and it's effect on paper properties.

2.3 Nip dimensions

In this thesis the x-direction is taken as parallel to the machine direction (MD), the y-direction is taken as parallel to the machine width or cross-machine direction (CD), and the z-direction is taken as parallel to the nip height or the paper thickness. The applied pressure in the press nip works in the z-direction.

A nip is formed by the contact area between two superimposed rolls and nip has the following dimensions:
- Nip height: the distance between the rolls parallel to the z-direction.
- Nip length: the contact length with the paper in the machine direction.
- Machine width.

Unlike nips in polymer converting, in wet pressing the nip height is not fixed. The rolls are pressed together by forces applied to the roll shafts. The applied load is fixed, so the nip length and height result from the compressibility of the material between the rolls. The nip geometry and the compressibility of the rolls, the felt, and the web, determine the width of the pressure profile. The applied load determines the maximum pressure that can be reached in the nip. Since rolls, felt(s), belt and paper web all move at the same speed through the nip the applied load is essentially unidirectional.

If the nip is made up using two non-compressible rolls, the nip is the contact line between these two rolls, while the applied load equals the load applied to the paper on that line. In practice the rolls deform significantly, or they are fitted with a rubber cover that deforms significantly, resulting in a nip length of several millimetres even without the presence of felt and paper. Consequently, the load applied to the paper is applied over a larger area resulting in a finite pressure.

Veenstra has shown that during calendering the actual pressure profile to which the paper is subjected is a result of both the geometry of the press and the mechanical

behaviour of the paper (Veenstra 2001). The pressure in the calendar nip is described by the Hertz laws (Szabo et al. 1974), the hardness of the cover, and the mechanical behaviour of the web. During calendering the web properties may differ significantly before and after compression. In these cases the pressure profile is not likely to be symmetrical.

Veenstra's work applied to calendering. The situation during wet-pressing is significantly different, since a felt moves with the web through the nip. Therefore, the actual pressure profile is the result of the same factors that affect the calendering process and the mechanical behaviour of the felt. Rolls may be assumed to compact and deform elastically. Felts and web deform visco-elastically (El-Hosseiny 1990; El-Hosseiny 1991). Veenstra has shown that the visco-elastic behaviour of paper alone can significantly affect the applied pressure profile during calendering (Veenstra 2001). During wet-pressing the deformation of the paper is far more significant, not to mention the hysteresis occurring in felts during compression and expansion. Therefore, the pressure profile can never be symmetrical.

The aim of this work is to provide a good description of the mechanical behaviour of the wet sheet. Ultimately this will enable the applied pressure curve to be calculated on the basis of a description of the combined mechanical behaviour of the rolls, the cover(s), the felt(s) and the paper.

A graphical representation of the first attempt to describe the mechanical behaviour of the wet sheet is given in figure 2-7. This figure shows the graphical representation of the wet-pressing theory presented by Nilsson and Larsson (Nilsson and Larsson 1968). We will use this theory as a starting point for our own work. A detailed description of figure 2-7 is given in the following sections.

The top part of this figure shows a schematic diagram of a nip formed by two rolls. In the nip we can see the paper web moving from left to right. The web enters the nip supported by the felt.

The press nip is the part where the paper, the felt and the rolls are in contact. As mentioned before, the rolls are pressed together. This means that the applied load is at its maximum at mid nip, i.e. the point at which the rolls are in closest contact. The applied load increases strongly as the web moves towards mid-nip, and decreases as it moves past mid-nip. This is indicated by the upper pressure profile plotted below the press nip. The pressure profile is divided into 4 zones.

For each zone the Terzaghi principle[4] is assumed to apply. This means that the applied load equals the sum of the hydraulic pressure and the structural pressure, i.e. the deformation stress in the web.

The four zones are:

1. Saturation of the wet sheet. In this zone the hydraulic pressure is insignificant. The full load is counteracted by the structural pressure, causing compaction of the web.
2. Compaction of the saturated sheet. The hydraulic pressure reaches it's maximum in this zone. Depending on the flow resistance met by the water, the hydraulic pressure in this zone can be higher or lower than the structural pressure. If the hydraulic pressure is higher than the structural pressure, the compaction is flow-controlled. This occurs for example at the entrance of the first nip when a lot of water is being removed. If the structural pressure is highest the flow regime is called compression-controlled. The flow in the last nip normally is compression-controlled.
3. Compaction of the wet web while pressure is being relieved. The rate of dewatering decreases. However, water is still being removed from the web by the applied load, because the time to mid nip is too short to reach the equilibrium moisture content.
4. Expansion of the wet web. The deformation stress of the wet web is assumed to decrease slower than the applied load, causing an under pressure in the web. This is the historical explanation of rewet and is called in-nip rewet. Currently, the significance of rewet in the nip is being denied (MacGregor 1989).

As mentioned above, the compaction during wet-pressing is proportional to the part of the load, deforming the web. The question is whether the compaction during wet-pressing also determines the effect wet-pressing has on the density of the web after wet-pressing. This aspect is addressed in chapter 4.

Based on their calculations, Nilsson and Larsson warned for the occurrence of compaction gradients, causing two-sidedness (Nilsson and Larsson 1968). They reasoned that if the Terzaghi principle applies, the sum of the hydraulic and structural pressure has to equal the applied load at any height in the paper. In event of a high gradient occurring in the hydraulic pressure due to low flow resistance at the felt side and high flow resistance at the roll side, the Terzaghi principle requires the existence of an equally high gradient in the structural pressure in a direction opposing the gradient in the hydraulic pressure. This should cause a deformation gradient over the z-direction of the paper. In 1983 Wicks and Szikla measured the occurrence of a density gradient under controlled conditions (Szikla 1992; Wicks 1985). MacGregor explained press felt marking and two-sidedness by this phenomenon combined with

| [4] The Terzaghi principle and it's implications for wet-pressing are described in detail in chapter 3, paragraph 3.

the relocation of fillers and fines by the water moving out of the sheet (MacGregor 1983). Szikla determined the exact conditions under which relocation of fillers and fines may occur (Szikla and Paulapuro 1987).

2.4 Pore dimensions

The dewatering theory of Nilsson and Larsson as described in the previous paragraph implicitly assumes that all water is located between the fibres, or that there is no difference between the water inside the fibres and the water between the fibres. In the following we will focus on the differences between the void fraction inside and between the fibres. The void space formed by the pores between the fibres is called the inter-fibre pore space and these pores are called the inter-fibre pores. The void space formed by the pores within the fibre walls is called the intra-fibre pore space and these pores are called the intra-fibre pores.

Maloney and co-workers reported pore size distribution of both the inter-fibre and intra-fibre pores (Maloney et al. 1997). Their measurements were an estimate based on volumes of water that could be removed by centrifuging. According to these measurements the pore size of the inter-fibre pores of bleached kraft softwood (BKSW) fibres ranges between twenty and several hundreds of micrometers.

Kettle and co-workers studied the effect of different calendering methods on the pore size distribution of a typical super calendered (SC) grade (30% kaolin filler and pulp consisting of 18% by weight chemical pulp and 82% by weight mechanical pulp, 53 g/m^2). They found that the combined results of air absorption and mercury porosimetry data provided them with the most representative pore size distribution. According to their measurements pore sizes between 40 and 200 micron are mainly a measure for surface roughness (Kettle et al. 1993). They found that before calendering about half of the pore volume was divided into three pore size distributions the pore diameters of which ranged from 40 to 100 micron, from 25 to 40 micron, and from 0.1 to 25 micron, respectively. After calendering, only one pore size distribution remained, ranging from 0.1 to 40 micron. Unfortunately, they did not study the effect of wet-pressing on the pore size distribution. The effect of wet-pressing on the inter-fibre pore space is investigated in chapter 7 using mercury porosimetry.

Maloney and co-workers also studied the intra-fibre pore size distribution. They used the following indirect measuring techniques:

- Nuclear Magnetic Resonance (NMR), and
- Solute Exclusion (SE) techniques.

According to these measurements the intra-fibre pores range from 5 to 40 nanometer (10^{-9} meter), depending on pulp type and pressing history (Maloney et al. 1997). This contradicts the current understanding of flow from the intra-fibre pores, for the following reasons:

First of all, the general opinion is that dewatering of inter-fibre pores can be described in terms of convective flow (Darcy equation) because it is fast enough to occur in the short nip residence time of commercial machines. The size of the intra-fibre pores as reported by Maloney is in the range were a fluid cannot be regarded as a continuum anymore. But even if one describes flow in terms of a continuum with such small pores the flow resistance becomes too high to allow for significant flow to occur during the nip residence time. Transport of material in a non-continuum is generally assumed to be slower than flow by convection in a continuum. Therefore, non-continuum transport from the intra-fibre pores becomes rather unlikely given the short nip residence times of commercial machines.

Furthermore, the reported intra-fibre pore-size distribution ignores the fact that in softwood pores are often visible using a normal light microscope, which means that they are tens of microns wide. We therefore assume that the intra-fibre pores range between the nanometer range reported by Maloney and co-workers and the microns range visible in softwood fibres under a light microscope.

Currently, a lot of effort is put into studying the exact geometry of a small piece of paper using a combination of microtomography and image analysis techniques (Auran et al. 1999; Gregersen and Niskanen 1999). The exact pore geometry at each moment during wet pressing remains impossible to measure.

An exact geometry would allow us to determine the actual flow velocity within the sheet as well as the actual stresses within the web. As mentioned before, the load applied to the web is unidirectional. However, in the contact point of two particles a normal force and a shear force can be transmitted. If unidirectional force is transferred from one particle to another, and if these particles do not have perfectly flat parallel surfaces, part of the applied force may be diverted to shear forces. If these shear forces exceed a certain value, i.e. the yield stress, the particles will start to slide over each other. This will lead to relatively large deformations.

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3 Macro scale modelling and paper-making

3.1 Introduction

When studying wet-pressing performance, both the compaction and the superficial flow are of interest. To estimate flow velocity the Darcy equation appears to be most appropriate (Jewett 1984; Mulder and Riepen 1994; Nilsson and Larsson 1968). To estimate the deformation stress the so-called Terzaghi principle appears to be well established in wet pressing (Campbell 1947; Mulder and Riepen 1994; Nilsson and Larsson 1968).

Both equations estimate on a macro scale average values of flow velocity and deformation stress, respectively. This means that the actual flow velocity within the pores, and the exact deformation stress in each fibre part, i.e. on a micro scale are scaled up to the macro scale of a sheet. This is done by applying the theory of homogenisation and void fraction theory. These theories can only be applied to systems that meet specific criteria. Therefore, in the following we will provide brief explanation of the homogenisation theory, the void fraction theory, the Darcy equation and the Terzaghi principle. We will also discuss the basic assumptions made about the wet paper structure when applying these equations to calculate wet-pressing performance.

Researchers at the Univeristy of Maine Ontario (UMO) dewatering project have suggested that capillary forces be included in the Terzaghi principle (Jewett 1984). However, their experiments showed that the capillary forces were not significant. We will look at these capillary forces when discussing the Terzaghi principle and provide an explanation why we do not expect them to play a significant role in this equation.

3.2 Homogenisation and void fraction theory

Homogenisation and void fraction theory form the link between the equations describing the actual forces and flow velocities occurring in a porous medium and the equations used to estimate the average stresses and superficial flow velocity in a porous medium. In other words it is the theory allowing to scale effects from micro to macro scale.

3.2.1 Homogenisation theory

The basic assumption underlying homogenisation theory is that the different phases present in a porous medium are homogeneously distributed throughout the volume of the porous medium. The distribution of the different phases in the medium occurs to such an extent, that each phase is assumed to exist in the same place.

This means that the homogenisation theory allows us to regard the porous medium as a multiple continuum with certain measurable average material characteristics, rather than a number of different phases, each with their own material characteristics and connected in a very complex (almost immeasurable) way.

To successfully apply the homogenisation theory the following boundary condition has to be met: the micro scale, i.e. the scale at which the different phases occur as single continua, should be small compared with the macro scale, i.e. the scale at which the averaged values are measured. For a saturated wet web, this implies that the width of the pores and the width of the fibre walls should be small compared with the sheet height.

This boundary condition dictates a minimum size of the volume in which the average flow and deformation are determined. This minimum volume required to determine representative experimental results is called the representative elementary volume (REV). One of the methods used to determine whether a sample volume is sufficiently high to act as an REV, is to determine whether it's permeability (cf. paragraph 3.4) does not change when the REV is increased. If the dimensions of the sample are smaller than required for the REV, the outcome of the measurements will be a function of volume of the REV. The REV is sufficiently high when increasing the volume does not change the outcome of the measurements.

The advantage of homogenisation is that the exact geometry of the structure does not need to be known. The disadvantage is that, instead of the calculation of actual forces and flow velocities on specific places in the porous structure, average forces and superficial flow velocities are estimated. In other words, the accuracy of the calculated result is traded for practical applicability.

3.2.2 Void fraction theory

The material characteristics of a multiple homogeneous medium are not only determined by the constituents of the multiple homogeneous medium, i.e. the

different phases that occur in the medium, but also by the ratio in which they occur. Therefore, the average void fractions in which the different phases occur are determined per REV.

The sum of the fractions in the porous medium should be one.

$$\Sigma\phi_i = 1 \qquad \textit{equation 3-1}$$

For an unsaturated wet web with water in the fibre walls, i.e. intra-fibre water, and water and air between the fibres, i.e. inter-fibre water and air, this can be written as:

$$\phi_n + \phi_f + \phi_S = 1 \qquad \textit{equation 3-2}$$

In which ϕ_n represents the void fraction between the fibres, i.e. the volume fraction made up by the inter-fibre pore volume [m^3/m^3], ϕ_f is the void fraction within the fibre walls, i.e. the volume fraction made up by the intra-fibre pore volume [m^3/m^3], and ϕ_S is the solid fraction [m^3/m^3]. Both the intra-fibre and the inter-fibre void fraction may be filled with water, air or a mixture of these depending on the degree of saturation of the network.

In the current dewatering models, $1-\phi_S$ is called the void fraction and treated as one phase (Gustafsson et al. 2001; Jewett 1984; Mulder and Riepen 1994; Riepen 2000).

3.2.3 Example

If we are interested in calculating the flow through the inter-fibre pores, we need to determine the inter-fibre void volume. Therefore, we consider the intra-fibre pores and the fibres as solid and the inter-fibre pores as void fraction. This is illustrated by image analysis work carried out by Niskanen and Rajatora (Niskanen and Rajatora 2002). As a way to determine a statistical approach to the exact 3D geometry of a dry piece of paper they digitalised pictures of the cross-sections and measured pore heights of the inter-fibre voids, cf. figure 3-1. In the picture on the left side of this figure there are fibres, inter-fibre voids, and intra-fibre voids, while in in the picture on the right side of figure 3-1 the fibres were regarded as solid structures, simplifying the picture to a two-phase system. By measuring the void and solid areas, the void fraction can be determined (void volume over total volume).

The next step is to assume that the fibres and the voids are evenly distributed throughout the porous medium while the void fraction remains constant. This means that the total void volume and the total fibre volume are the same as before homogenisation, but distributed in a more even way, cf. figure 3-2. According to the homogenisation theory the distribution of the solid and void fractions in the medium occurs to such an extent, that the fluid and solid fractions exist in the same place. Therefore, this is often referred to as double continuous medium; a continuous solid and a continuous void phase are assumed because on the scale of observation we cannot distinguish between the solid and void phases.

3.3 Terzaghi principle

The Terzaghi principle estimates the effective stress in the solid phase making up the porous medium as a function of the total distributed load and the hydraulic pressure in the water. The effective stress in the solid phase causes the compaction of the porous medium.

$$\sigma_E = \sigma_T - p_H \qquad \textit{equation 3-3}$$

In which σ_E represents the effective stress per square metre area resulting from the deformation of the solid structure [Pa], σ_T represents the total load applied per surface area [Pa], and p_H is the hydraulic pressure [Pa]. In paper the effective stress is referred to as the structural pressure of the web, p_S.

3.3.1 Void fractions and compressible fibres

From the moment that Terzaghi first published his principle the following question has been asked (Boer et al. 1996; Carlsson 1983):
Why does the Terzaghi principle not include void fractions, like a force balance on the micro scale is supposed to do, cf. equation 3-4?

$$F_T = (1 - \phi)\, F_S + \phi\, F_V \qquad \textit{equation 3-4}$$

In which F_T represents the total applied load to the cross section [N], ϕ is the void fraction [m^3/m^3], F_S is the load applied to the solid part of the cross section [N], and F_V is the load applied to the void part of the cross section [N].

The answer to this question is in the homogenisation theory. To understand this we may consider a porous medium made of incompressible particles and saturated with water, for example a water-saturated clay soil.

A volume of 20 cm^3 of water-saturated clay soil may be considered as an REV for this soil. When applying the homogenisation theory to this volume, we implicitly assume that the water phase and the solid phase both are continuous and therefore both fill the complete volume of the REV. This means that the load is applied to the total surface of the REV and that the hydraulic pressure counteracts the applied load across the entire surface of the REV. Therefore, void fractions do not apply. It also explains why it is so important that the micro scale is very small compared with the macro scale.

In the above we considered a water-saturated clay soil, instead of a water saturated web. We did so because clay particles may be considered incompressible, while fibres may compact significantly during wet-pressing. However, the Terzaghi principle is a simplification of a more generally applicable equation. Because of this simplification the Terzaghi principle applies only to incompressible particles. If the particles of the porous medium show significant deformation, this consumes part of the applied load. If the estimate for the structural pressure is not corrected for this effect, the estimate for the sheet compaction will be too high. Therefore, Biot suggested the addition of a correction factor to the hydraulic pressure (Biot 1956).

$$\sigma_T = p_S + \alpha\, p_H \qquad \textit{equation 3-5}$$

In which σ_T represents the total load applied on the surface area [Pa], p_S is the structural pressure resulting from the deformation of the solid structure, i.e. the effective stress [Pa], α is a constant to account for the compressibility of the fluid and the solid particles making up the porous medium [-] , and p_H is the hydraulic pressure [Pa].

However, for paper fibres the calculation of α is quite difficult since the compressibility of the fibres varies strongly with the type of fibre (Scallan and Tigerström 1992), and decreases with decreasing water content. Therefore, we would like to suggest a more direct approach: estimating the fibre compaction based on the dewatering data, cf. chapter 8.

3.3.2 Buoyancy, gravitation, and inertia forces

According to the Terzaghi Principle the total applied load to the wet web equals the stress in the wet paper. This implies that gravitation, buoyancy and inertia forces are insignificant.

Comparing the mass involved with the loads applied in the press nips, it is clear that buoyancy and gravitation forces can be neglected as soon as the wet web enters the nip. For example, the absolute maximum for extremely heavy board is 1.0 kg/m^2 dry weight, i.e. 5.0 kg/m^2 maximum wet weight, equalling 50 Pa while the loads applied in the press nips vary between 1.0 and 12 MPa.

Inertia forces do not depend solely on the weight of the web, but also on the reaction time to the application of a pulse. If the reaction time to a pressure pulse is low compared with the nip residence time, inertia forces will be insignificant.

The reaction time is determined as the time it takes for a pressure pulse to travel through the web from the roll to the felt side. To estimate the reaction time, we have assumed that the propagation speed of sound is a good measure for the reaction time to a pressure pulse, since sound also is a form of pressure pulse. Therefore, the speed at which sound moves through the web is a good estimate for the speed at which the pressure pulse may move through the web.

Table 3-1: Physical properties of water and cellulose webs

Entity	**Symbol**	**Value**	**[Units]**
Temperature	T	60	^{o}C
Water density (T)	ρ_w	983	kg/m^3
Water viscosity (T)	μ_w	$4.66 \cdot 10^{-4}$	Pa s
Surface tension (T) water against air	γ_w	$6.618 \cdot 10^{-2}$	N/m
Propagation speed of sound(T) in air	c_a	350	m/s
Propagation speed of sound(T) in water	c_w	1551	m/s
Propagation speed of sound(T) in dry cellulose fibres	c_{dcf}	$1.8 \cdot 10^3$ - $3.6 \cdot 10^3$ (Chatterjee 2001)	m/s

Table 3-1 lists the speed at which sounds travel through water and through dry cellulose. Since the speed of travelling through water is lowest, we will assume the speed at which sound travels through water. Assuming a maximum sheet thickness of 5 millimetres, it will take the pressure pulse about 0.003 milliseconds to travel from the roll to the felt side which even at record machine speeds is insignificant compared with the nip residence time. Therefore, we may assume that inertia forces may be neglected.

From the above we may conclude that the boundary conditions that have to be met before the Terzaghi principle may be applied are as follows:

- The medium should be homogeneous at the scale of observation
- Inertia forces, gravitation, and buoyancy forces should be insignificant compared with the difference between the applied load and the hydraulic pressure
- The particles should be incompressible and in point contact only, or the equation will need modification (Biot 1956; Kataja et al. 1995).

3.4 Darcy equation for flow

The Darcy equation allows for the estimation of the superficial flow velocity as a function of the flow resistance met by the fluid and the hydraulic pressure gradient experienced by the fluid.

$$v = -\frac{K}{\mu}\frac{\partial p_H}{\partial z} \qquad \textit{equation 3-6}$$

In which v represents the superficial flow velocity of the fluid flowing through the sheet [m/s], K is the permeability of the medium to the fluid [m^2], μ is the viscosity of the fluid [Pa.s], $\partial p_H / \partial z$ is the hydraulic pressure gradient over the thickness [Pa/m].

The hydraulic pressure is the stress experienced by the fluid, or in other words, the part of the total distributed load that is balanced by the fluid. If the water is in contact with places were the hydraulic pressure is lower, the difference in hydraulic pressure may be used to overcome flow resistance.

According to the Darcy equation the permeability is a material constant. However, if we rewrite the Kozeny equation in terms of the Darcy equation we find the permeability as a function of the tortuosity, the active surface, and the void fraction available to flow.

$$v = - \frac{K}{\mu} \frac{\partial p_H}{\partial z}$$

$$K = \frac{1}{\tau S^2} \frac{\phi^3}{(1-\phi)^2} \qquad \textit{equation 3-7}$$

In which τ is a constant to correct for the tortuosity of the pores [m/m], S is the active surface area per unit volume of solid material [m^2/m^3], and ϕ is the volume fraction available to flow [m^3/m^3].

Lindsay (Lindsay 1997) was the first to suggest that the Kozeny equation applies to paper, provided that one distinguishes between the void fraction available to flow and the overall porosity.

3.4.1 Tortuosity, void fraction and active surface

The Darcy equation is very similar to Poisseuille's equation, except for the fact that we have to deal with a far more complex geometry. To take this complex geometry into account the permeability is a function of tortuosity, void fraction and active surface. This can be easily understood when one realises that the permeability is a measure of the friction caused by the interaction between the fluid and the wall.

The void fraction available to flow accounts for the effect of the total volume available to flow. The higher the volume, the lower the flow resistance, the limiting values being no flow if no void fraction is present, and minimal flow resistance if no solid fraction is present, i.e. if the void volume available to flow equals 1. Void fraction can be determined using image analysis techniques in combination with pictures of cross sections of paper (Gregersen and Niskanen 1999; Niskanen and Rajatora 2002). The inter-fibre void fraction available to flow can be determined using mercury porosimetry, cf. chapter 7, or by determining sample weight, water content, fibre water content, and the density of the fibrous material. The latter method is applied in this thesis, cf. chapter 4.

Tortuosity accounts for the effect of the pore geometry. Straight pores will cause a far lower flow resistance than curling and twisting pores. A method has recently become available to estimate the tortuosity of a dried sheet using microtomography, image analysis and Monte-Carlo simulations (Gupta et al. 2003).

The active surface is a way to take into account the chemical interaction between the filler, the fibre surfaces and the water. In theory the active surface of a dry sheet can be determined by measuring gas absorption and calculating the BET isotherm (Atkins 1990). However, in practice this is less straight forward as it seems. Experimental studies on catalyst beds have shown that the product of the tortuosity and the active surface is proportional to a characteristic cross-sectional area of the pores (Bird et al. 1960), cf. chapter 7.

3.4.2 Permeability and REV

Darcy found that the flow of water through a sand layer is a function of the pressure difference over this layer and the ratio of it's permeability to water and the viscosity of the water. The viscosity of a fluid is a material characteristic that is influenced by the temperature of the fluid alone. The permeability is a function of the porosity of the sand layer, but independent of the thickness of the sand layer. However, starting with a layer of sand that is only one grain thick, the flow measured across will be higher than that across a layer of two grains. The difference becomes smaller and smaller, to eventually disappear. The volume at which the permeability does not further decrease with increasing layer thickness is the REV.

Vomhoff has carefully determined this point (Vomhoff 1998), cf. figure 3-3. This figure shows the effect of adding additional layers on the permeability. At first the permeability decreases linearly with increasing base weight to finally become independent of base weight. The only conclusion that may be drawn based on this figure is that the REV requires a base weight of 200-250 g/m^2. This indicates that paper is in fact too thin to apply the homogenisation theory. Therefore, using the Darcy equation on paper is not self-evident. The validity of deriving a three-parameter-equation for the permeability to describe local effects due to press unevenness as presented by Vomhoff should be questioned (Vomhoff 1998). In our opinion such effects cannot be described in terms of permeability.

Nevertheless, the homogenisation theory has been applied successfully to paper to predict dewatering rates. This can be explained as follows. Applying the homogenisation theory on samples that are too thin has the following drawback's.

- The permeability becomes a function of base weight.
- The standard deviation on the calculated superficial flow velocity increases with decreasing base weight.

The dewatering models still may predict the dewatering rate quite accurately because of the wide web widths used in commercial paper production, which even out variations in the dewatering rate. This means that in practice the Darcy equation can be applied if the permeability is determined on the exact felt sheet combination used on the paper machine.

However, when experimentally determining the permeability of a sheet one should be aware of the porous structure of fibres. As discussed in chapters 6 and 7, fibre dewatering does occur during wet-pressing and since the pore size of the intra-fibre pores is significantly lower than the pore size of the inter-fibre pores, significantly different values should apply to either the inter-fibre pore space and the intra-fibre pore space. Measuring the permeability of a sheet by measuring the superficial flow velocity through a sheet of paper yields either an effective value of the permeability or, in the best case, the permeability of the inter-fibre pores alone. Therefore, a different method is required to determine the separate values for the permeability of both the inter-fibre and intra-fibre pore spaces.

3.4.3 Reynolds and Darcy

The Darcy equation may only be applied if the flow through the porous medium is laminar, i.e. parallel flow lines without turbulences. This means that the Reynolds number should be lower than 10 and preferably lower than 1. The Reynolds number is calculated based on the characteristics of the actual flow in the pores, using the following equation:

$$Re = \frac{2\rho \, v_{fs} \, r}{\eta} \qquad \textit{equation 3-8}$$

In which ρ represents the density of the fluid [kg/m^3], v_{fs} is the actual flow velocity of the fluid compared with the solids , i.e. the pore wall [m/s], r is the characteristic pore radius [m], and η is the fluid's viscosity at the temperature in the pore [Pa s].

Since we do not know the actual pore geometry nor the actual flow velocity we will try to estimate the conditions under which the highest Reynolds number is likely to occur and the flow velocity occurring under these circumstances.

During wet-pressing the wet web passes through several nips. The highest change for turbulent flow occurs at the entrance of the first nip because at this point the pores are still wide and the web is still saturated with water.

Another factor affecting the type of flow is the temperature. Both the viscosity and the density of water decrease with rising temperature, cf. figure 3-4. However, the viscosity changes more than the density in the range up to 60 °C. Therefore, the highest changes for a high Reynolds number is at a temperature of 60 °C. The density of water at 60 °C is 983.23 kg/m^3 and the dynamic viscosity is 0.466 Pa s.

The characteristic pore diameter is determined in chapter 7, r = 3.5 micron or less.

To estimate the flow velocity in the pore, we first estimate the maximum superficial flow velocity. The maximum amount of water that may be removed in the first nip is estimated to occur when dewatering a 100 g/m^2 web from a dry content of 25% to 33% (the base weight should not be too low because in that case there is not enough hydraulic pressure to build up speed, nor too high because this results in excess flow resistance).

This implies the removal of 100 g/m^2 water in one nip. The nip residence time is 2 milliseconds (20 mm at 600 m/min, faster machines are expected to need more or longer nips). This results in an estimated value for the superficial flow velocity of v = 0.05 m/s.

The actual flow velocity of the fluid relative to the pore walls depends on the void fraction available to the flow and the tortuosity of the pores.

$$v_{fs} = \frac{\tau\, v}{\phi_n} \qquad \textit{equation 3-9}$$

In which v_{fs} represents the actual flow velocity of the fluid compared with the pore wall [m/s], τ is the tortuosity of the pores [-], v is the superficial flow velocity [m/s], and ϕ_n is the void fraction available to flow in the inter-fibre pores.

The void fraction available to flow in the inter-fibre pores equals the total void fraction minus the void fraction within the fibres. Carlsson has shown that the void fraction within the fibres can be closely estimated using the water retention value (WRV), cf. chapter 6 (Carlsson et al. 1977). The minimum WRV reported for unpressed fibres is about 1 kg/kg. For a saturated web with a dry content of 25% this results in a void fraction available to flow equal to 0.75.

The value for the tortuosity is a factor indicating how much longer the actual flow path is, compared with the height of the web. Gupta and co-workers (Gupta et al.

2003) have reported tortuosity values for pressed and dried sheets as a function of the total sheet porosity. According to these results the tortuosity is already well below 2 at a porosity of 0.5. To make sure that our estimate is conservative we will assume the tortuosity to be 2.

Based on the above we estimate that the maximum actual flow velocity that may occur in a nip, v_{fs} = 0.13 m/s, resulting in a maximum Reynolds number at 60 °C of Re = 0.002. From this we may safely assume that the flow will be laminar under all relevant conditions, as required to apply the Darcy equation.

3.5 Capillary effects

Air bubbles may form within the water contained in the pores. However, the air is expected to leave the sheet almost instantly after pressure is applied because of the following characteristics of air bubbles.

- Air is compressible, the application of a load will result in density gradients in the air-water mixture. Under the influence of these density gradients air will move to the lower density areas.
- The viscosity of air, is significantly lower than the viscosity of water, allowing a much higher flow velocity of air compared with the surrounding water.

If a bubble blocks a pore, before the water can continue it first has to flow along the walls to separate the air from the wall (Roberts et al. 2003).

Since we expect the air-bubbles to leave the sheet at the entrance of the nip, bubble deformation does not form a significant part of the reaction forces to the applied load. Therefore, capillary action is not a reaction to the applied load and thus needs not be taken into account in this force balance.

In the case of under saturation at the entrance of the nip, we assume that the air and water are mostly separated and that the presence of air means that there is less space for the water to flow through the medium. Additionally, the air phase has a lower viscosity and is compressible, unlike the water phase. Michaels has shown that the effect of under saturation on permeability can be taken into account by additional saturation equations (Michaels 1960). He estimated that the presence of air would have the following effect on the permeability of the medium to water and air, respectively.

$$K_w = K\, s^4$$
$$K_a = K\,(1-s)^3\ (1 + 3s) \qquad \textit{equation 3-10}$$

Where K is the permeability in case of 100% saturation of either air or water [m^2], the subscripts *a* and *w* indicate air and water, respectively, and *s* stands for the degree of saturation [m^3/m^3].

The importance of capillary action within wet sheets is that it is a strong force, keeping the narrow pores saturated even at low moisture contents.

3.6 Conclusions

Homogenisation and void fraction theory are the link between the equations describing the actual forces and flow velocities occurring in a porous medium on micro scale and the equations used to estimate the average stresses and superficial flow velocity in media on macro scale, i.e. it is the theory that allows us to scale-up form the micro scale to macro scale. These theories are essential for understanding the Darcy equation and the Terzaghi principle.

The Terzaghi principle estimates the effective stress in the incompressible particles making up the porous medium, as a function of the total distributed load and the hydraulic pressure in the water. The effective stress in the solid phase causes the compaction of the porous medium. In paper the effective stress is referred to as the structural pressure of the web, P_S. Furthermore, the total applied stress equals the load applied in the nip since buoyancy, gravitation and inertia forces can be neglected.

The compressibility of paper fibres cannot be neglected. This should be taken into account when applying the Terzaghi principle. Biot has suggested a correction factor. An alternative approach would be to determine the deformation of the fibres separately from the deformation of the fibre network, and then write the deformation equation as the sum of the network and the fibre deformation. The latter option will be worked out in chapter 8.

An additional advantage of this alternative approach is that separate calculation of the deformation of the fibres allows for the separate calculation of the hydraulic pressure over the fibre wall and thus it enables us to explicitly calculate the fibre dewatering.

The Darcy equation calculates the superficial flow rate of the dewatering of the wet web. To apply the Darcy equation the following boundary conditions should be met.

- Flow through the porous medium should be laminar. According to our estimates of the flow velocity in the wet web, this is always the case in wet-pressing.
- The thickness of the web should be sufficiently high for a representative elementary volume (REV). This is not the case for the low base weights of paper. However, we expect that the Darcy equation still can be applied. Applying the Darcy equation on base weights below 200 g/m^2 has the following disadvantages: The permeability becomes a function of base weight and the variations in the paper will be higher than in the board. However, because of the wide paper machine width this effect is expected to even out over the paper width.

When applying the Darcy equation to the flow from the wet web without differentiating between inter-fibre and intra-fibre dewatering, an effective permeability is calculated. This permeability does not show a significant correlation with the total void fraction. When separating inter-fibre and intra-fibre flow, the flow of the inter-fibre pores has a permeability that is a function of the inter-fibre void fraction as described by the Kozeny equation, cf. chapter 7.

According to experimentally determined relations on catalyst beds, the inter-fibre permeability may also be a function of the characteristic cross section of the inter-fibre pores. The question is whether one can distinguish such a characteristic cross section, cf. chapter 7.

The presence of air may change the flow characteristics of the air-water mixture compared with 100% water. However, macroscopic equations exist to correct the flow characteristics for the presence of air. The Terzaghi and Darcy equations need no fundamental alterations when air is present.

3.7 References

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4 Compaction

4.1 Background

Local variations in paper properties are generally regarded as degrading the paper quality. However, the significance of such local variations may differ with the degree of variation and the application of the paper or board. For example local density differences as caused by felt marking[1] are always degrading the quality. However, the importance of felt marking can change significantly per paper or board grade. For a box lining, felt marking may be regarded as insignificant as long as the strength properties of the board are not affected. For printing paper the same degree of felt marking may not be acceptable since it significantly degrades the paper's appearance and printability. The quality of paper and board is determined by the combination of paper properties resulting from bulk and surface characteristics and how these properties enable the paper to perform in specific applications.

Wet-pressing changes both the average degree of compaction and the local variation in compaction. This affects both the overall value of paper properties and the local variation in paper properties (Busker 1985; Busker 1986; Dahl 1989; Lavery 1987; MacGregor 1983; MacGregor 1989; Wahlstrom 1989).

Density is a quantitative measure for the compactness of a structure and therefore density changes are a natural measure to determine compaction changes. Density is known to affect many paper properties. The question is how an increase in density can be used to determine the effect of wet-pressing on paper properties, followed by the questions which mechanisms determine the effect of wet-pressing on density, and how this effect may be quantified.

4.2 Theory on compaction and wet-pressing

Density is a measure for the compactness of a structure and therefore also a measure for the void fraction within the paper structure and within the fibres. The total void space in the paper and the gradients in the void space determine the openness of the paper to the transport of fluids and gasses. Additionally, the distance between the fibres of the network affects the degree of bonding that is possible and therefore has a strong effect on paper strength. Furthermore, the void fraction has a strong effect on

[1] Felt marking refers to local differences in density caused by the structure of the felt. Felt marking is visible as local differences in whiteness. For more information on felts, see chapter 2

thickness and consequently stiffness properties.

In view of the above we expected strong correlations between the effect of wet-pressing on paper properties and the density of the paper. Therefore, we measured the density, and some representative properties that relate strongly to the effects described in the above, to determine experimentally the correlation between density and paper properties. The results will be discussed in paragraph 4.5.

However, we questioned the effectiveness of the density of the dry sheet as a measure for the compaction during wet-pressing, since after wet-pressing the paper may undergo a number of treatments that may affect the density like drying and calandering, but that have nothing to do with the effect of wet-pressing on the density. In the case of strength properties, a density increase due to calandering is known to decrease instead of increase the strength properties of the paper. Therefore, we also determined the density of the wet sheet directly after wet-pressing.

Furthermore, we attempted to gain insight into the mechanisms determining the compaction during wet-pressing, and to develop a quantitative description of these phenomena. The current understanding of wet-pressing is qualitative, apart from a number of quantitative models, existing within the paper-making industry. However, these models are not described in the open literature. Furthermore we expect them to be empirical, i.e. determined by trial and error. As a result these models are valid only for the machine-furnish combinations they have been derived from, and need revision in the event of changes to the machine or the stock preparation.

Therefore, it is important to know which factors determine the sheet compaction. In the literature we found different factors listed.

Dahl (Dahl 1989) stated that the main factors affecting sheet compactions are:
- Press impulse
- Deformation resistance of the web
- Single-felted or double-felted nip (less important)

This list agrees with common sense. However, only a few years earlier Busker carried out an experimental study for the interaction between wet-pressing parameters and compaction, which resulted in a different list (Busker 1985; Busker 1986). He did not report pressure as a significant factor, but instead he reported that the density of the dry paper was a function of the following factors:

- Furnish type
- Outgoing dry content
- Configuration of the press section (i.e. shoe press or roll press).

Additionally, Busker reported that during evaporative drying the density increased linearly with dry content.

Therefore, according to Busker's experimental results the outgoing dry content after wet-pressing correlated strongly with the apparent density of the dry paper regardless of the applied pressure. Furthermore, press sections consisting of only roll nips yielded higher dry densities than press sections comprising an extended nip press (ENP) pressing to the same dry content.

If the conclusions drawn by Busker were correct, this means that the press impulse had no effect on the apparent density of the dried sheet. The question is, how can we explain Busker's observations?

From Busker's observations we drew the following conclusions:
- The dry apparent density varied with the dry content after wet pressing. Apparently, the water content at mid nip was of no influence.
- The press section comprising only roll nip presses yielded a higher dry apparent density than the press section comprising an ENP whereas both press sections dewatered to the same outgoing dry content. Apparently the wet-pressing history influenced the final result.
- Furnishes made of chemically pulped fibres tend to have higher dry apparent density than furnishes made of mechanically pulped fibres. Apparently, the deformation resistance of the fibre was of importance.

During evaporative drying the sheet density increased linearly with dry content. Apparently, the wet and the dry density were strongly related. Based on these conclusions we developed the following hypothesis:

The net effect of wet-pressing is reflected in the apparent density of the wet web directly after leaving the nip, i.e. the wet apparent density. The density of the wet web is expected to be determined by the expansion of the wet sheet. Apparently, expansion is a function of moisture content and fibre wall stiffness.

A way to disproof this hypothesis, is to compress two samples in exactly the same way, but to allow for different expansion conditions. If the compaction of the dried samples turns out to be identical, the hypothesis will have been proven false.

4.3 Experimental

The general set-up consisted of the following parts:

- Compaction of two furnishes made of two very different types of fibres: thermo-mechanical pulp (TMP), and bleached kraft hard wood pulp (BKHW).
- Pressing the furnishes to completion by a known pressure pulse at a low and a high pressure (0.5 and 4.0 MPa).
- Pressing the furnishes to completion between solid plates, i.e. xy-dewatering, or against a porous plate, i.e. z-dewatering. In the first case rewet was prevented, in the second case rewet was possible and did occur.
- Determining representative properties of the dried samples: i.e. the dry apparent density, air permeance and z-tensile strength (Dahl 1989; Lavery 1987).

4.3.1 Furnishes

All tests were carried out on hand sheets made of two different types of virgin fibres: thermo-mechanical pulp (TMP), and bleached kraft hard wood pulp (BKHW). The TMP was produced at the Norske Skog-Parenco newsprint mill and air dried at TNO, the BKHW was obtained as dry bales. After dispersing, the BKHW was beaten for 1500 rounds at minimum pressure in an Imset differential Mühle für Imitationsmahlung (Imset differential laboratory refiner).

The pulp was divided in two portions. Half of the pulp was used directly to make hand sheets. The other half was first washed over a sieve (mesh 250 micron) before the pulp was used to make hand sheets. The aim of the washing was to remove a significant part of the fines present in the pulp.

Hand sheets were made using a Rapid Köthen sheet former. The sheets were made of the fresh pulps shortly before the tests and stored in a refrigerator until the test.

Just before the test circular samples were cut from the hand sheets, using the Zwick Kniehebelpresse in combination with a circular knife of 79.8 mm diameter.

4.3.2 Structural pressure curve

The experimental determination of the structural pressure was based on the Terzaghi principle. The Terzaghi principle states that the applied load equals the sum of the structural pressure and the hydraulic pressure.

This means that if the value for the hydraulic pressure approaches zero, the structural pressure approaches the applied load. By determining the void fraction the structural pressure can be determined as a function of the void fraction under equilibrium conditions. This relation describes the maximum dry content of a web after wet pressing as a function of the applied load.

The void fraction was determined by measuring the minimum sheet thickness during compaction, weighing the total sheet weight directly after compaction and weighing the bone dry sheet weight after drying. Based on these measurements the void fraction could be determined by assuming sheet saturation during compaction. An important factor affecting the reproducibility of these measurements was rewet, which therefore had to be prevented from occurring. If rewet is prevented, the structural-pressure curve appears to provide relevant information on the compaction.

4.3.3 Equipment

Figure 4-1 shows the Zwick Z020 Material tester, which was used for the compression and expansion tests. The Zwick Z020 is a spindle machine, i.e. it is designed for static compression and accurate thickness measurements. The pressure pulse was preset and applied automatically, cf. figure 4-2 and figure 4-3. The only aspect that was changed was the value of the maximum pressure.

The samples were dewatered in both lateral and transversal direction. During lateral dewatering the sample was dewatered between two smooth solid plates. The lateral dewatering time was set to at least 600 seconds. This compression time should be sufficient to press the samples to completion (Paulapuro 2001; Wilder 1960). During transversal dewatering the solid bottom plate was replaced by a porous plate, made of sintered brass. The plate being porous, water could be expressed in the z-direction through the porous surface. This significantly reduced the flow path of the water. Therefore, the transversal dewatering time was assumed to be much shorter, and the holding time was reduced to only 100 seconds. The porous surface was supported by a perforated plate, allowing excess water to move out of the porous plate into

the perforations. The perforations were interconnected, allowing for redistribution of excess water. The porous plate was regularly dried to make sure that saturation would not affect transversal dewatering. Only when two saturated samples had been compressed to 4.0 MPa in succession, water remained present in the perforations, otherwise no proof was visible of the presence of water. From this we concluded that the construction used had sufficient water storage capacity.

Because of the type of equipment used, loading and unloading took sufficient time to allow for rewet. During the transversal dewatering rewet occurred because the porous plate was not connected to a vacuum system to prevent rewet. During the lateral dewatering rewet was prevented by the application of tissues to absorb the water flowing from the samples.

Directly after expansion the samples were weighed to obtain a good indication of the wet content in the samples, with and without rewet. Some samples were compressed for a second time, using the same method as used for the samples that were compressed for the first time.

The samples were subsequently dried for at least 3 hours at 105 °C. After drying the samples were conditioned at 23 °C +/-1 °C and 50% +/-2% relative humidity for at least 12 hours, to enable the apparent dry density, the air permeance, and the z-tensile strength to be measured. All paper properties were measured in a room conditioned according to ISO 187.

The thickness of each sample was assumed to equal the difference between a measurement without a sample that was made immediately prior to the measurements with samples. To guarantee proper contact with the actuator during expansion, the samples were allowed to expand at a minimal load of 50 N.

4.4 Reproducibility

Because of the extreme precision necessary in this type of measurement, the reproducibility of the measurements was meticulously checked before interpreting the measurements.

4.4.1 Thickness readings

The registration without sample was called a blank and measured directly before or directly after the measurement with sample. We used the blanks to determine the reproducibility of the thickness readings We found that the thickness readings were affected by deformation of the equipment. We found the following causes for equipment deformation.

- Application of a higher load than previously applied. The most probable cause of this type of the deformation of the testing equipment was the ejection of lubricant to protect the joints of the testing equipment.
- Changing from lateral to transversal dewatering and vice versa. To change from lateral to transversal dewatering the supporting plate had to be changed from solid to porous (and vice versa). Since this was carried out by hand, the exact starting position could not be reproduced, cf. figure 4-4 and figure 4-6.
- In addition to the normal causes described above, small errors could occur, resulting in outliers. Figure 4-6 clearly shows that measurement no. 9 was an outlier. Since blanks nos. 7 and 11 matched the other measurements, only measurements nos. 8 and 10 were considered biased. Therefore, measurements nos. 8-10 were ignored for the evaluation of the experimental data.

Nevertheless, the position readings obtained from both the lateral and the transversal dewatering tests were reproducible within 0.5 micron, cf. figure 4-5 and the transversal dewatering blanks, cf. figure 4-7. Since the thickness readings were obtained as the difference of the position readings with and without sample, the sample thickness readings were assumed to be reproducible within 1 micron.

4.4.2 Pressure curve

As described in paragraph 4.3.3 the pressure was applied using a preset pressure profile. The reproducibility of the applied pressure profiles was high.

The maximum pressure was achieved at a relatively high speed resulting in an unwanted overshoot. Nevertheless, the maximal deviation was 0.60% for a 0.5 MPa structural pressure, and 0.25% for a 4.0 MPa structural pressure.

4.4.3 Apparent density

The apparent density of the wet and the dry paper were determined. In both cases

the apparent density was calculated by dividing the weight of the dry sample, by the sample area and by the average sample thickness.

The weight of the dry sample was determined after drying and conditioning 23 °C +/-1 °C and 50% +/-2% relative humidity for at least 12 hours. The sample area was assumed to equal the size of the cut sample, i.e. 50 cm^2.

The thickness of the wet samples was obtained by determining the distance between the compressing surfaces at the end of the expansion curve at a compression load of 50 N.

The thickness of the dry samples was determined by measuring the samples thickness according to ISO 534 using a L&W instrument, i.e at 0.1 MPa pressure. On each sample four thickness measurements were taken: three evenly distributed over the outer 1.5 centimetres of the sample and one in the centre. The average value of the thickness measurements was used for the density calculation.

4.4.4 Air permeance

The permeability of the final paper to air was measured using the Bendtsen apparatus, in accordance with ISO standard 5636/3. The sample was compressed between two soft rings enclosing the sample surface and air was forced to flow through the sample. The surface area available to the air flow was determined by the size of the ring, and equalled 1000 mm^2. The Bendtsen apparatus measures an airflow, q, at a certain pressure, p. The air is kept at a reference pressure of 1.47 kPa. The air permeance is linearly related to q according to equation 4-1.

$$Air\ permeance = \frac{q}{60\ A_{ring} P} = 0.0113\ q \qquad \text{equation 4-1}$$

In which 60 is used to convert time [min] to time [s], A_{ring} represents the surface area under the ring through which the air is allowed to flow [mm^2], q is the flow under the ring through the paper [ml/min], and p is the pressure at which the air flows through the paper [kPa].

The air permeance according to the Bendtsen method is expressed in [µm/(Pa s)].

4.4.5 Z-tensile strength

The z-tensile strength was measured on a Zwick machine. The samples were taped to the sample holder using double-sided adhesive tape, and compressed with a force of 900 N during 6 seconds. After removing the pressure force, the samples were torn apart at a speed of 100 mm/min (Tappi standard T541 om-89).

4.5 Results

The question is whether the density of the wet sheet (the wet apparent density), is a better indicator for compaction during wet-pressing than the density of the dry sheet (the dry apparent density). Therefore, we plotted the wet apparent density against the dry apparent density of single pressed TMP samples, cf. figure 4-8. The dry apparent density appeared to equal the wet apparent density. Adding samples that were twice compressed caused additional deviation but did not significantly alter the relation, cf. figure 4-9.

This means that in the case of TMP the effect of drying was insignificant. Unlike the normal procedure with commercial machines, the only treatment we applied to the paper after wet pressing was drying. Therefore, in the case of TMP the dry and the wet apparent density gave the same impression of the effect of wet pressing on the samples. However, during fractionation a significant amount of fines was removed from the TMP samples, allowing for the comparison of the effect of fines with the effect of wet-pressing on the paper properties.

In case of the BKHW samples the situation was slightly different, cf. figure 4-10. The dry density of the BKHW appeared to be significantly higher than the wet density of the BKHW. This illustrated a well known phenomenon, occurring when drying chemically pulped fibres: drying shrinkage. Nevertheless, there was a strong correlation between the dry and the wet apparent density.

For BKHW, drying changed the paper structure and therefore one property could correlate stronger to the dry apparent density than to the wet apparent density, allowing us to determine which effect were more important; the changes made to the structure during wet-pressing or the final structure as obtained after drying.

This was illustrated by the measurements of the paper properties. Figure 4-11 shows

the Z-tensile strength measured for the BKHW samples as a function of the wet apparent density. The Z-tensile strength correlated better to the wet apparent density than to the dry apparent density. This can be easily understood if we consider that the Z-tensile strength is the result of bonds between the fibres in adjacent layers. These layers can only form bonds if they are in close enough contact. The higher the degree of compaction, the more opportunities there are for fibre bonding, and thus the higher the measured tensile strength. Apart from the compaction, the formation of inter-fibre bonds depends heavily on the chemical and physical structure of the fibre wall. Therefore, the Z-tensile strength can vary strongly between furnishes that have been compacted to the same extent.

Figure 4-12 illustrates the effect of fines content on the Z-tensile strength of TMP samples. The samples containing fines appeared to have a higher Z-tensile strength than the samples made of fractionated pulp, but the increase in Z-tensile strength with increasing density was the same for the samples with fines as for the samples without fines. This shows that changes to the geometry that cause decreasing bonding opportunities (as in case of the removal of fines) did not affect the results of wet-pressing on this strength property.

Figure 4-13 shows the air permeance of the BKHW samples as a function of the wet apparent density. Figure 4-14 shows the air permeance of the same samples as a function of the dry apparent density. Comparison of the figures shows that the air permeance correlated stronger to the dry apparent density. This was to be expected since the actual flow resistance met by the air is determined by the pore size in the finished sheet and not by the pore size after wet pressing.

The importance of the exact pore size geometry was also reflected by the effect of fines on the air permeance of TMP. Figure 4-15 shows the air permeance of TMP samples with and without fines as a function of the dry apparent density. At the same density the air permeance of the samples containing fines was significantly lower than that of the fractionated samples, but more importantly, the decrease in air permeance with increasing density was far higher for the samples without fines than for the samples with fines. Apparently, the fines had a greater effect on the flow resistance of the paper to the air than that caused by the compaction due to wet pressing.

In view of the above we may conclude that the density is changed by wet pressing and that the wet apparent density is the best measure for the effect of wet-pressing on the compaction of the paper. The question that remains is; which wet pressing parameters affect the compaction?

To check the effect of pressure on the density of the dry sheet, the apparent density of the dry sample was plotted as a function of the applied pressure, cf. figure 4-16. The pressure appeared to have a significant effect when comparing the dry apparent density of the samples were rewet was not possible, i.e. the laterally dewatered samples. However, in case where rewet was possible, i.e. the transversal dewatered samples, pressure appeared to have little or no effect. Similar trends were measured for BKHW. From this we concluded that the applied pressure did not determine the final dry apparent density.

When plotting the same density data as a function of the dry content after wet pressing, the dry apparent density appeared to be a linear function of the outgoing dry content, cf. figure 4-17. Figure 4-17 clearly shows that the outgoing dry content had a stronger effect on density than the applied pressure. This confirmed the observation reported by Busker that dry apparent density was a function of the outgoing dry content, not of the applied pressure.

4.6 Conclusions

We carried out experiments to determine the feasibility of quantitatively predicting the effect of wet pressing on paper properties. The experimental results indicated that the wet apparent density is a good indicator. It correlated well with the changes in paper properties with increasing compaction due to wet pressing and it cannot be affected by process steps following wet pressing as in the case of the dry apparent density.

We found a strong correlation between wet and dry apparent density. Nevertheless, the Z-tensile strength correlated better to the wet apparent density than to the dry apparent density, whereas the air permeance correlated better to the dry apparent density.

The Z-tensile strength depends on the fibre-fibre bonding across the sheet thickness. Therefore we concluded that the good correlation between the Z-tensile strength and the wet apparent density implies that the compaction resulting from wet pressing caused extra fibre-fibre bonding, whereas the compaction during drying did not significantly add to the fibre-fibre bonding.

The fact that the correlation between the air permeance and the dry apparent density is higher than the correlation between the air permeance and the wet apparent density may be explained by the dependence of the air permeance on the flow resistance. The flow resistance depends on the actual pore geometry and this geometry apparently shrank during drying.

Furthermore, the experimental results confirmed the results reported by Busker. The outgoing dry content showed a strong correlation with the dry apparent density independent of press impulse. Therefore, we may assume that a good prediction of the dewatering of a wet web is the starting point for a good prediction of the final compaction of the wet web. From the experimental work we may conclude that wet density is the best indicator for the effect of wet pressing on dry density and other paper properties.

4.7 References

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5 Rewet and felt coarseness

5.1 Introduction

This chapter presents experimental results that are not in line with the so-called Differentiated Permeability Surface Layer (DPSL) theory presented by I'Anson and Ashworth (I'Anson and Ashworth 2000), and it presents a new theory explaining the relation between felt coarseness and the moisture content after wet pressing.

I'Anson and Ashworth carried out wet-pressing experiments to determine the effect of felt surface structure on final moisture ratio after wet pressing. The experiments were carried out on two types of light base weight hand sheets, mechanically pulped fibres referred to as LWC sheets on the one hand, and bleached chemically pulped fibres referred to as wood-free hand sheets on the other. They calculated the rewet by applying the method described by McDonald and Kerekes (Kerekes and McDonald 1991; MacDonald and Kerekes 1991; MacDonald and Kerekes 1995), cf. equation 5-1. They found a strong correlation between felt coarseness and rewet.

$$MR = MR_0 + \frac{R}{BW}$$

$$MR_0 = MR_{in}\left[1 + \frac{A\, n\, MR_{in}^{n}\, I}{BW^2}\right]^{\frac{-1}{n}} \qquad \textit{equation 5-1}$$

In which MR represents the outgoing moisture ratio after wet-pressing [kg/kg], MR_0 is the minimal moisture ratio in the nip [kg/kg], R is the amount of rewet [g/m^2], and BW represents the base weight [g/m^2]. MR_0 is estimated from the ingoing moisture ratio [kg/kg] MR_{in}, the permeability coefficient A [g^2/(m^4 kPa s)], the compressibility factor n [-], and the press impulse I [kPa s].

From a data set of outgoing moisture ratio at varying base weight the amount of rewet occurring in a certain nip configuration can be obtained by plotting the MR to the reciprocal of the BW. McDonald and Kerekes have suggested that n equals 3 for most type of furnishes. This means that, starting with I'Anson and Ashworth's data set, the only unknown variable in equation 5-1 is the permeability factor A. After calculating A they found that this permeability factor correlated well with the felt coarseness, especially in the case of LWC sheets.

Since one type of furnish of one base weight should have one permeability factor they assumed that felt coarseness had to be included in a formula predicting rewet.

Earlier Vomhoff compared the effect of a coarse felt on a wet web with compressing foam rubber with an iron wire (Vomhoff 1998). A pile of foam layers alternating in colour was pressed while photographs were taken to determine the effect of the felt coarseness on the compaction behaviour. Vomhoff concluded that: "... the traditional assumption of uniform pressure transfer at the web-felt interface is unrealistic, as the peculiarities of the web/felt interaction are neglected."

Using this conclusion, I'Anson and Ashworth developed a theory to explain the relation between the calculated rewet and the felt coarseness. This theory was called the Differentiated Permeability Surface Layer (DPSL) theory. The name refers to the assumed effect of the felt coarseness on the structure of the web's surface layer, cf. figure 5-1. They assumed a very strong densification directly under a point were the felt touches the web and a very open structure on the places were there is no direct contact between felt and web. These high density areas are assumed to increase in depth and width with increasing felt coarseness. The very dense areas are supposed to have a very low permeability, the open areas a very high permeability and the intermediate areas an intermediate permeability. Therefore, it was called the differentiated surface permeability layer. Only the layer(s) below the differentiated surface permeability area were supposed to be pressed evenly and to have a constant permeability.

They found that the differences in outgoing moisture ratio showed a good correlation with the estimated size of the high permeability areas, i.e. the size of the non-pressed parts of the surface. Based on this correlation they assumed that the water causing the difference between MR and MR_0 had never left the sample but had always been present in the high permeability areas in their samples.

Szikla and Palonkangas (Szikla and Palokangas 1991) measured differences in compaction in the upper layer of the sheet due to felt surface unevenness. We accept the assumption that the thickness of this layer may vary with the felt coarseness. However, we do not expect that the effect of felt coarseness can be enough to explain the difference in water content after wet-pressing as reported by I'Anson and Ashworth. In the following we will explain why.

The foam used by Vomhoff (Vomhoff 1998) is a fairly homogeneous material (regarding the scale of the experiments). Paper in contrary has a fibrous structure and is therefore an inhomogeneous material. If foam is pressed, the point to which a load is being applied has to withstand this load. If a load is applied to paper, the load is applied to a fibre rather than a point. The load applied to a fibre is distributed over the total fibre surface and the surfaces of the fibres connected to the stressed fibre. Therefore, a load applied to paper will be carried by a much larger surface than a load applied to foam. Consequently, the differences in compaction between the point directly below the applied load and the surrounding area will be much more gradual than will be the case with foam. To illustrate the difference, consider the following thought experiment. Imagine pressing your fork onto a plate-full of mashed potatoes. The fork will quickly descend to the plate. Now repeat the experiment, but this time with a plate-full of spaghetti. You will have to smash the spaghetti before your fork can make significant progress.

Because of the difference in compaction behaviour of homogeneous and fibrous materials, we consider the explanation suggested by I'Anson and Ashworth unlikely. Since we do not question the experimental data provided by them, we have developed a different theory. Our theory explains the experimental results reported by I'Anson and Ashworth, and also takes into account the effect of the fibres on the compaction behaviour of the paper.

5.2 New theory

Paper is a fibrous material. Consequently an applied load will be diverted if the paper surface is pressed at any one point, causing not only that point to deform, but a whole network. The degree to which the applied load is diverted sideways depends on a number of variables:

- The stiffness of the fibre; a very stiff fibre will distribute the load almost evenly along it's length, while an elastic fibre will deform mainly at the point where the load is applied.
- The length of the fibre; fibre stiffness being equal, a long fibre will divert the load more than a short fibre.
- The bonding between the fibre to which the force is applied and the other fibres of the network. With strong bonds part of the load may be distributed among a number of fibres. With weak bonds the fibre to which the load is applied has to support the load on it's own.

- The compaction of the web; in a compacted web every fibre is supported by other fibres and fibre bonding is more frequent, allowing for good distribution of the applied load.

Thus, depending on the type of furnish and the degree of compaction, there will be differences in the degree of surface compressibility of the wet web. To some extent local compaction will occur; otherwise phenomena like felt marking would not exist.

Therefore, we agree that felt coarseness may cause local differences in compaction. Nevertheless, we think that the large length of most fibres compared to the sheet thickness will make the local differences in compaction too small to explain the observed effect of felt coarseness on calculated rewet.

Additionally, I'Anson and Ashworth reported that the effect of the felt coarseness on the amount of water that remained in the sheet was stronger for LWC than for wood-free samples. LWC has the highest percentage of coarse fibres and is therefore less likely to show local differences in compaction.

Therefore, we expect to find that felt coarseness rather increases void space outside the web at the interface between felt and web, than increasing void space within the web. We assume that the size of these void areas is a function of felt coarseness and local compressibility of the web's surface. It seems likely that the size of the void spaces increases with felt coarseness and decreasing web compressibility. We have therefore named this theory the felt coarseness rewet (FCR) theory.

The FCR theory explains the same phenomena as those reported by I'Anson and Ashworth. Both theories suggest that felt coarseness should be decreased in order to decrease rewet. However, the underlying mechanisms are fundamentally different, allowing different strategies for wet-pressing optimisation.

Both theories agree on the following. If you take two identical samples and you press them to completion, the final moisture ratio may differ, depending on felt coarseness. The moisture ratio will increase with increasing roughness of the felt compared to the thickness and the compressibility of the sample. However, the DPSL theory assumes that the difference in moisture content is water that has never left the web. Thus if a sheet is pressed twice under exactly the same conditions apart from a very thin plastic film in between the sheet and the felt, inhibiting the flow from and back into the sheet, the final moisture ratios should be the same. There are no indications in the

DPSL theory that the effect of replacing transversal dewatering by lateral dewatering should cause any problem, provided that the dewatering time is sufficient to dewater the sheet to completion.

According to the new FCR theory the water moves from the sheet into the voids and back. Therefore the final water content will be higher than in the case of dewatering with the plastic film. The differences that we expect to find according to the FCR theory with and without the plastic film are depicted in figure 5-2.

The validity of either theory can be tested by carrying out the tests described above.

5.3 Experimental

5.3.1 Variables

The purpose of the experiments described in this chapter was to determine whether back flow of water occurs during in-nip rewet.

Samples were pressed in two different ways:
1. Directly to the felt so water could freely flow into and out of the felt.
2. Against the felt while a thin pliable film (polyethylene) inhibited flow into and out of the felt.

The effect of the felt coarseness was taken into account by using both a smooth and a coarse felt. Normally, in wet-pressing experiments, a felt has to be run in to ensure that the experimental results are representative for actual use. In these experiments we used felts that had not been used before, in order to ensure the greatest possible difference between the surface structures of the felts.

The samples were made of hand sheets differing in two aspects:
1. Furnish type: thermo-mechanical pulp (TMP), and bleached kraft hard wood pulp (BKHW).
2. Base weight: low base weight 50-55 g/m^2 and high base weight 155-160 g/m^2.

The TMP was produced at the Norske Skog-Parenco newsprint mill and air dried at TNO, the BKHW was obtained in the form of dry bales . After dispersing, the pulps were immediately used to prepare the samples. The freeness of the pulps was

determined in a Schopper-Riegler test. The TMP had a freeness of 68-70 SR, while the BKHW had a freeness of 27 SR (Schopper-Riegler units). Hand sheets were made using a Rapid Köthen sheet former. The sheets were made with the fresh pulps shortly before the tests and stored in a refrigerator until the test. Just before the test, circular samples with a surface area of 100 cm^2 were cut from the sheets.

For reference purposes, samples were pressed to completion between very smooth aluminium surfaces while any kind of rewet was inhibited.

5.3.2 Compaction test

To ensure that both the samples pressed with and those without plastic film were dewatered to the same extent all samples were pressed to completion.

The samples were pressed in a hand-driven screw press. The pressure was increased by reducing the distance between the face plates rather than by applying a specific load. The load required to realise a certain thickness reduction was registered by means of a force sensor connected to a personal computer (PC). The sample was pressed to completion, and the stress at completion was registered. This stress is also referred to as the structural pressure. Samples were pressed against a felt for 15 minutes at pressures varying from 0.03 to 3.0 MPa, which was considered to ensure completion (Paulapuro 2001).

After pressing, the samples were weighted and dried in a flat-bed oven dryer for at least three hours at 105 ^oC to enable the moisture ratio at the measured structural pressure to be calculated.

5.4 Results

The purpose of the experiments was to verify the validity of the felt coarseness rewet (FCR) theory. Therefore, we pressed both low and high basis-weight samples to completion against a coarse and a fine felt. As a reference samples were pressed to completion against an extremely smooth aluminium surface, while any form of backflow to the samples was inhibited.

The experiments were carried out on samples cut from TMP and BKHW sheets. In the figures the applied pressure is expressed in bar, which corresponds to 10^5 Pa, or 10^{-1} MPa.

This approach showed a strong relation between outgoing moisture ratio and the smoothness of the surfaces against which the samples were pressed. Figure 5-3 shows the results obtained on 150 g/m^2 TMP samples. The outgoing moisture ratio of the samples pressed against the coarse felt at each pressure was significantly higher than the outgoing moisture ratio of the samples pressed against the fine felt. No significant difference in moisture ratio of the samples pressed against the fine felt and the samples pressed against a smooth nonporous surface was observed.

For the BKHW samples, cf. figure 5-4, slightly different results were measured. At elevated pressures the samples pressed against the fine felt had a higher outgoing moisture ratio than had the samples pressed against the smooth aluminium surface, the latter representing the equilibrium moisture content of the sample pressed to completion without rewet. At low pressures no significant difference in moisture ratio of the samples pressed against the fine felt and of the samples pressed against the smooth surface was observed.

The 50 g/m^2 TMP samples also showed a strong relation between outgoing moisture ratio and the surface smoothness. The measured outgoing moisture ratio did not significantly differ from the outgoing moisture ratio of the 150 g/m^2 TMP samples, cf. figure 5-5.

The actual outgoing moisture ratio of the BKHW samples pressed against the coarse felt could not be determined because the samples disintegrated as a result of the high outgoing moisture content, cf. figure 5-6. Therefore, it seems very likely that the 50 g/m^2 BKHW samples showed a strong correlation between felt coarseness and outgoing moisture ratio.

From the above we may conclude that, if sheets are pressed directly against a felt, i.e. if backflow from the felt is possible, the relation between felt coarseness and outgoing moisture ratio can be reproduced.

The reported increase in moisture ratio with decreasing base weight was not observed. However, I'Anson and Ashworth (I'Anson and Ashworth 2000) reported the occurrence of this effect on sheets ranging from 30-60 g/m^2, while we used 50 and 150 g/m^2 sheets. So it may well be that the effect of base weight decreases at higher base weights, as used in these experiments. It is also possible that it becomes insignificant compared with the effect of felt coarseness, since we used extremely coarse felts.

If the DPSL theory is correct, the outgoing moisture ratio decreases with increasing smoothness of the surface applying the load to the sample. Furthermore, the effect should be stronger in case of lightweight samples than in case of heavy samples. To test this hypothesis we pressed samples to completion against the fine felt and the coarse felt while any form of rewet was inhibited.

The results are plotted in figure 5-7. Contrary to the experiments during which back flow of water from the felt was possible, the measured moisture ratios on 150 g/m^2 TMP samples were independent of felt coarseness. In samples pressed to completion while back flow from the felt was inhibited, the outgoing moisture ratio appeared to be a function only of the applied pressure and the furnish type.

To test the effect of the base weight, 50 g/m^2 TMP samples were also pressed to completion against the fine and the coarse felt, while rewet was inhibited, as in the case of the 150 g/m^2 samples. In figure 5-8 the moisture ratios of the 50 g/m^2 samples are plotted in a single graph with the results measured on the 150 g/m^2 TMP samples.

At low pressures no significant difference was measured, but at high pressure the moisture ratio of the 50 g/m^2 TMP samples was significantly higher than the moisture ratio of the 150 g/m^2 TMP samples, cf. figure 5-8. However, no significant difference could be observed between the 50 g/m^2 samples pressed against the impermeable coarse felt and the 50 g/m^2 samples pressed against the impermeable fine felt.

The same tests were carried out on BKHW samples.

For the 150 g/m^2 samples no significant effect of felt coarseness was observed on the outgoing moisture ratio of BKHW samples pressed to completion between two impermeable surfaces, cf. figure 5-9.

For the 50 g/m^2 samples a slightly higher outgoing moisture ratio was observed for the samples pressed to the coarse felt surface, but only at elevated pressures. The 50 g/m^2 samples pressed against the surface of a fine felt did not show a significant higher moisture ratio than the 150 g/m^2 samples at any pressure, cf. figure 5-10.

Therefore, when backflow from the felt was prevented, no significant effect of felt coarseness could be observed. For TMP fibres after compaction to completion at

elevated pressure, on the 50 g/m^2 samples a significantly higher outgoing moisture ratio was measured than on the 150 g/m^2 samples. No significant difference was measured for BKHW samples.

The DPSL theory does not provide an explanation for these measurements. We suggest the following explanation.

When a wet sheet is pressed, voids will occur between the surface applying the force, i.e. the felt or roll surface, and the sheet's surface. The size of these voids is expected to vary with the following factors:
- The felt coarseness, the roll cover, or the roll.
- The flexibility of the sheet's surface.

We therefore named this theory the felt coarseness rewet (FCR) theory.

This theory explains the phenomena as reported by I'Anson and Ashworth, and in addition it explains the differences measured with and without allowing backflow of water from the felt.

5.5 Conclusions

The calculation method for predicting rewet as developed by I'Anson and Ashworth, i.e. the DPSL pressing theory, is the first theory to take felt coarseness into account. As we have shown this parameter is likely to have a significant effect on the final dry content after wet-pressing. Although we share their view that the felt coarseness compared with the sheet's thickness is an important parameter, we do not agree with their explanation. Furthermore we were able to show that, contrary to the DPSL pressing theory, backflow is necessary to reproduce the effect of felt coarseness as predicted by the DPSL pressing theory. Our experimental results negate the assumption made in the DPSL theory that the difference is due to higher water retention resulting from sheet surface permeability gradients.

Accordingly, a new theory for understanding the effect of felt coarseness on outgoing moisture ratio is presented. This theory is in agreement with the results presented earlier by I'Anson and Ashworth, and it can also explain why these results could not be reproduced when backflow from the felt was inhibited.

The new theory states that felt coarseness increases void spaces outside the sheet at the interface between felt and sheet rather than increasing void spaces within the sheet. The size of these voids is expected to be a function of felt coarseness and local compressibility of the sheet's surface. This theory is called the felt coarseness rewet (FCR) theory.

The theory combines the new insights into the effect of felt coarseness on outgoing moisture ratio reported by I'Anson and Ashworth, with the specific mechanical behaviour of fibrous materials under compaction as pointed out at the start of this article.

The FCR theory implies that a good estimate of the void space between sheet and felt may provide a good estimate of the rewet.

5.6 References

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6 Measuring the fibre dewatering potential

6.1 Introduction

During wet pressing part of the water that may leave the wet web is known to be located within the fibre walls (Carlsson et al. 1977; Maloney et al. 1997). This water has to overcome a higher flow resistance than the water located between the fibres. Therefore, it is interesting to know which part of the water that may be removed by increasing the applied pressure originates from the fibre walls.

A technique providing the required data is the solute exclusion technique (Carlsson et al. 1977). In this technique, polymers of different sizes are added to the sample. During dewatering the concentration of these polymers in the water pressed form the sample is measured, giving an indication of the size of the pores being dewatered. From this size distribution the minimal force may be calculated that is required to make the water available. However, the solute exclusion method is rather laborious and requires specialist techniques.

Maloney (Maloney and Paulapuro 1999) reported the centrifugal compression value (CCV) test as a means to determining the intra-fibre water content as a function of the applied load. In this test a pulp sample is centrifuged while being compressed by a weight sitting on top of the sample. By measuring samples at different loads a CCV-curve is obtained. This method has been used to determine the intra-fibre water content as a function of the applied for various types of furnishes. The CCV test as reported by Maloney provides information on the dewatering characteristics of fibre pads, which not necessarily correlate with the dewatering characteristics of sheets. Additionally no validation of the outcomes of this test method was published. Therefore, in addition to the structural-pressure curve test discussed in chapter 4, a new test was developed, the water-retention curve. This curve is determined by measuring the water retention value (WRV) of samples after they have been compressed for determining the structural-pressure curve. In this way the water-retention curve was measured as an extension to the structural-pressure curve measurement.

To interpret the outcomes of the water-retention curve, this curve was determined in combination with the structural-pressure curve for a number of furnishes which show considerable variation in dewatering behaviour. The results were compared both with each other, and to the values obtained with CCV tests on a TMP hand sheet.

6.2 Working principle of water-retention curve test

The WRV measurement is based on the centrifugal force as a means of separating water from fibre material. A centrifuge is used to overcome the capillary action that keeps the water in the pores. The relation between capillary pressure and pore radius is given by equation 6-1.

$$P_c = \frac{2\gamma \cos\theta}{r} \qquad \textit{equation 6-1}$$

In which P_c represents the absolute pressure [N/m^2], γ is the surface tension [N/m], θ is the wetting angle [degrees], and r is the pore radius (or equivalent circular radius) [m]. Water wets the fibres, thus the factor cosθ = 1.

This means that the higher the force caused by the centrifuging, the smaller the pores that will be emptied.

The centrifuging force on the water is described by equation 6-2.

$$\frac{F_c}{A} = \frac{(2\pi\omega L)^2}{L}\frac{m_w}{A} = Gg\frac{m_w}{A} \qquad \textit{equation 6-2}$$

In which F_c represents the centripetal force on the water [N], A is the surface area across which the force on the water acts [m^2], ω is the angle speed in rounds per second [1/s], L is the distance from the centre of the centrifuge to the bottom of the filter cup [m], m_w is the mass of the water in the sample [kg], G represents the G-force resulting from the centrifuging [-], and g is the gravitational acceleration [m/s^2]. The product $2\pi\omega L$ equals the speed at which the sample moves in the centrifuge [m/s]

Instead of fibre pads of ca 1400 g/m^2, as used for determining the WRV, we used samples of hand sheets (50 cm^2 of 100g/m^2 hand sheets). The surface area of our cups was 56 mm^2 and the water mass of the samples was at least 0.3 g (60% dry content after wet pressing). At 23 ^{o}C the surface tension of water and air is 0.072 N/m.

To determine the required G-force we will assume that the minimum pore radius to be emptied by the centrifugal force is that at which the capillary action (equation 6-1) equals the centrifugal force (equation 6-2). This results in equation 6-3, which estimates the G-force required to empty all pores above a certain radius, r.

$$G = \frac{2\gamma A}{m_w r g} \qquad \textit{equation 6-3}$$

In which G represents the G-force caused by centrifuging speed [-], γ is the surface tension [N/m], A is the surface area on which the force acts on the water [m^2], m_w is the mass of water in the sample [kg], r is the pore radius (or equivalent circular radius) [m], and g is the gravitational acceleration [m/s^2].

According to the results presented in chapter 7, the maximum radius of the inter-fibre pores, i.e. the void spaces that will be emptied in this way, should be 1 micron. This results in a minimum G-force of 2700. To calculate this number we made some assumptions:

- The sample was regarded as a homogeneous solid-water mixture, instead of a folded inhomogeneous paper sample.
- The calculated values are based on average results, while ignoring strong deviations from the average that may occur locally.

Therefore, this number should be regarded as an estimate rather than a precisely calculated number. Nevertheless, it will allow us to determine which of the two generally applied methods for measuring the WRV is appropriate to our application: the Northern American method described by Tappi UM 256, or the European method described by ZellChemig Merkblatt IV/33/57. These test descriptions differ considerably in centrifuging time and centrifuging speed. The European ZellChemig IV/33/57 standard prescribes 3000 G during 10 minutes for unrefined pulp and 15 minutes for refined pulp.

The Tappi UM 256 standard prescribes 900 G during 30 minutes at 21 °C +/- 3 °C. The calculated minimum G force indicates that in this application only the ZellChemig standard will yield a good estimate for the intra-fibre water content. The ZellChemig standard was therefore used.

6.3 Experimental

6.3.1 Furnishes

The test were carried out on hand sheets made of four different types of pulp: thermo-mechanical pulp (TMP), low yield bleached kraft hard wood (BKHW) pulp, low yield bleached kraft soft wood (BKSW) pulp, and recycle pulp (B-grade).

The recycle pulp was obtained by repulping cardboard made of 100% B12 quality pulp in a laboratory table digester. The TMP was produced at the Norske Skog-Parenco newsprint mill and air-dried at TNO. The BKSW and the BKHW were obtained as dry bales. After dispersing the BKSW and the BKHW were lightly beaten in an Imset differential Mühle für Imitationsmahlung (i.e. Imset differential laboratory refiner). The BKHW was beaten for 5000 rounds and the BKSW was beaten for 1500-2000 rounds at minimum pressure.

Hand sheets were made using an 80 mesh sheet former. The sheets were made shortly before the tests using of the fresh pulps, covered with plastic, and stored in a refrigerator until the test.

Immediately before the test, circular samples were cut from the hand sheets using the Zwick Kniehebelpresse in combination with a circular knife with a diameter of 79.8 millimetre.

6.3.2 Structural-pressure and water-retention curve

The pressure pulse was preset and carried out automatically to guarantee a high reproducibility of the measurements. The only aspect to be changed was the value of the maximum pressure, cf. figure 6-1. The samples were compressed to completion at one pressure. The samples were compressed to completions by a certain pressure. For each type of sample data were collected at the following structural pressures: 0.1, 0.5, 1.0, 2.0, and 4.0 MPa. For each pressure a new sample was used.

The samples were dewatered in the lateral direction only (i.e. in the xy-plane) by compressing the sample between two solid surfaces. Any excess water was removed by absorption with tissues. The water forced out of the sheet was removed to prevent the occurrence of significant rewet during the expansion. The samples were dewatered in the xy-plane to guarantee homogeneous dewatering.

The samples were first weighed, after which they were preconditioned by compressing them to 0.1 MPa for 3 minutes. After preconditioning the press was opened, and the samples weighed again. The samples were then compressed again for 3 minutes at 0.1 MPa before the intended structural pressure was applied for 15 minutes. This compression time should be sufficient to press the samples to completion (Paulapuro 2001).
The final stress was assumed to equal the structural pressure exerted by the sample. To allow the moisture ratio to be determined, the samples were weighted directly after opening of the press.

After weighing, the water retention value (WRV) was measured by putting the compressed sample in a filter cup, sealing the cup with para-film, and centrifuging for 20 minutes at 4800 rpm (the maximum speed of our centrifuge). The distance between the bottom of the filter cup and the centre of the centrifuge was 0.11 metre. The moisture content before centrifuging varied between 6 and 0.8 kg/kg, and the dry weight of the samples varied between 0.4 and 0.7 gram. Therefore, the water content varied between 0.32 and 4.2 gram.

To determine the samples' dry weight, the samples were dried in an oven for at least three hours at 105 °C. Using the dry weight of the sample, both the equilibrium moisture ratio (MR), and the WRV at the structural pressure were calculated for each sample.

6.4 Results

The tests described above resulted in a number of data points per furnish, a representative example of which are the results obtained for TMP, as shown in figure 6-2. In the figures the applied pressure was expressed in bar, 1 bar = 0.1 MPa.

Before pressing, the sample underwent various minor stresses during formation and storage. The net effect of these pressures was estimated to equal a structural pressure of 0.1 bar (= 0.01 MPa). Therefore, the value of the x-axis starts at 0.1 bar. This also explains why the moisture ratios of the samples before wet-pressing were plotted at 0.1 bar.

Non-linear regression of the data shows that the structural-pressure curve can be fitted by a power function, cf. figure 6-2. This is in agreement with the data reported in literature (Mulder 1995; Nilsson and Larsson 1968).

Figure 6-3 shows the water retention values (WRVs) measured on TMP. The only available evaluation is comparison with the results yielded by Maloney's CCV test (Maloney and Paulapuro 1999). Therefore, the results of both methods were plotted in the same figure.

At pressures of 5 bar (0.5 MPa) and higher the measured values of both methods coincide. However, the measurements at low pressures were significantly different. This was not expected, since both methods centrifuge the samples at 4500 rpm.

Provided that in both cases the centrifuge radius was about 0.1 metre this should result in similar dewatering results. The only difference is that the pulp used was air-dried, whereas the CCV pulp was never dried.

However, Carlsson reported a WRV for never-dried TMP before wet pressing of 1.1-1.2 kg/kg (Carlsson 1983). This is in good agreement with the water-retention curve, indicating that the CCV method overestimates the WRV at low pressures, and that the centrifuging of pressed samples in our method gave a correct estimate of the fibre-water content.

Figure 6-4 shows the CCV values plotted together with the structural-pressure curve of TMP. The CCV appeared to better fit the results of the structural-pressure curve. Apparently, centrifuging during compression removes water less well than centrifuging after compression. This was probably due to one of the inherent advantages that the above presented method has over the CCV test. These inherent advantages are listed below.

Firstly, the pulp will not clog the filter, since it is formed and pressed before it is centrifuged.

Secondly, significant less water needs to be removed, since most of the water is removed while determining the moisture content. This makes it more likely that all superfluous water will be able to leave the sample during centrifuging.

Thirdly, the determination of the WRVs is truly additional to the structural-pressure curve, and no special equipment is required apart from glass filter cups and a sufficiently capable centrifuge. Specially designed cups are required for the CCV test (Maloney and Paulapuro 1999). Standard glass filter cups were prone to breaking.

6.5 Discussion

Now that we have determined that the experimental method yielded meaningful results, we can study the relation with the applied pressure. We tested a number of furnishes, and the measured values for the water retention fit the following relation with the structural pressure, cf. Table 1.

$$In\left\{\frac{WRV}{WRV_o}\right\} = -b\,p_S \qquad \textit{equation 6-4}$$

In which *WRV* represents the water retention value [kg/kg], WRV_0 is the water retention value before wet pressing [kg/kg], *b* is a material characteristic [m^2/N], and p_S is the structural pressure [N/m^2].

Table 1: Fitting to equation 6-5 of experimental data for a number of furnishes yielded these values for the fit parameters WRV_0 and b.

Furnish	$\boldsymbol{WRV_0}$ **[kg/kg]**	***b*** **[m^2/N]**
Tmp	1.13	$12.4 \cdot 10^{-8}$
60% B12 +40% B19	0.84	$2.5 \cdot 10^{-8}$
100% B12	0.92	$4.4 \cdot 10^{-8}$
100% B12 repulped	1.27	$4.9 \cdot 10^{-8}$
BKSW	1.56	$9.0 \cdot 10^{-8}$
BKHW	1.25	$13.2 \cdot 10^{-8}$

This means that the dewatering of the furnishes is proportional to the applied load. This is in agreement with common sense; volume decrease of the fibres is linearly related to the dewatering. This equation can be easily written in a general form of Hooke's law, which would imply that the fibres show elastic behaviour. However, this experimental set-up is to simple too allow for such generalisations.

Figure 6-5 shows that fibre dewatering became significant when most of the water in the sample was located inside the fibre wall, in other words, when the total water content of the sample approached the fibre water content, the fibres started to dewater. The pressure at which this occurred varied per furnish type. This is clearly visible when comparing the experimental results obtained for BKSW to the experimental results obtained for repulped B12 pulp. For the BKSW the fibre dewatering became significant at a pressure between 1.0 and 2.0 MPa. At 2.0 MPa (20 bar) all the water inside the sample was located within the fibres, cf. figure 6-7. For the repulped B12 fibres water still remained between the fibres even when the sample was compressed to completion by 4.0 MPa, cf. figure 6-6.

It is perfectly possible that under dynamic conditions, fibre dewatering will occur while there is still water between the fibres that lends itself to dewatering, provided that the drive for fibre dewatering is sufficiently high. We will return to this in chapter 8.

6.6 Conclusions

The water present in a wet web is divided over two different types of void fractions; the so-called inter-fibre and intra-fibre void fractions. The inter-fibre void fraction is formed by pores located in between the fibres, whereas the intra-fibre void fraction is formed by pores that are located inside the fibre wall. The pores making up these void fractions differ significantly in dimension. Because of this scale difference the intra-fibre void fraction is expected to be significantly less permeable to water than the inter-fibre pores. Therefore, a new and easy to use method was developed to separately determine the deformation of the intra-fibre pore space and the inter-fibre pore space as a function of the applied load.

This method provides a good indication of the dewaterability of a sample, since it not only shows how much water may be removed by an increase in pressure but also which part of the water has to be removed from the fibres.

After pressing to completion, the water content in the fibres appears to be an exponential function of the applied pressure. The fibres do not dewater significantly before all the water present in the pores between the fibres is removed. To determine whether this is due to high flow resistance in the fibre walls or lack of driving force, experiments under dynamic conditions will have to be carried out. This method may be helpful to determine the fibre water content after wet-pressing under dynamic conditions.

6.7 References

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7 Pore-size distribution

7.1 Introduction

Lindsay was the first to recognise that the Kozeny-Carman equation states that the permeability of a sheet correlates with the void fraction available to flow and that the void fraction available to flow does not equal the porosity of the sheet (Lindsay 1997). When taking this into account, the flow through a sheet can be described by the Kozeny-Carman equation. This has the advantage that engineering rules determined in other fields can be applied to paper-making. One of these engineering rules states that the permeability of a medium is a function of the void fraction and the characteristic pore radius (Bird et al. 1960).

This is a very practical rule. However, during wet-pressing the web is being compacted, and therefore the characteristic pore size may change. In chapter 6 we reported that the pore volume decreased due to compaction. In this chapter we will focus on the way in which the compaction changes the pore-size distribution, and the effect of this change on the permeability to water of a wet web.

For that purpose the pore-size distribution of TMP, refined and unrefined BKHW sheets, made on various formers, and compressed to different degrees of density, was determined using mercury porosimetry.

Mercury porosimetry is a widely applied method to determine pore-size distributions in various materials. In paper science this method has been used to determine for example the effect of refining on pore-size distribution of several fibre materials (Annus et al. 1999), and to determine the pore-size distribution of coatings.

We will apply this method to different furnishes to determine the following:
1. How does the degree of compaction change the pore-size distribution of a certain type of furnish?
2. Does the way in which the pore size changes depend on furnish characteristics?

In paragraph 7.2 the theory behind the experiments is explained. In paragraph 7.3 we explain the working principle of the mercury porosimetry method. This is followed by a paragraph on the experimental approach. In paragraphs 7.5 and 7.6 the results of the experiments are presented and discussed, and in paragraph 7.7 conclusions are drawn.

7.2 Flow in porous media

Paper is a porous medium. The Kozeny-Carman equation describes the flow of a fluid through a porous medium, cf. equation 7-1.

$$v = \frac{K\,\partial p_H}{\mu\ \partial z}$$

$$K = \frac{1}{\tau S_0^2}\ \frac{\phi^3}{(1-\phi)^2} \qquad \textit{equation 7-1}$$

In which v represents the superficial flow velocity through the porous medium [m/s], K is the permeability of the porous medium to a fluid [m^2], μ is the viscosity of the fluid, $\partial p_H / \partial z$ represents the hydraulic pressure gradient over the height of the porous medium [N/m^3], τ is a constant to correct for the tortuosity of the pores [m/m], S_0 is the surface area of the porous material in connection with the surface of the porous material per unit volume of solid material [m^{-1}], and ϕ represents the volume fraction available to flow [m^3/m^3].

Many authors have tried, unsuccessfully, to correlate the Kozeny-Carman equation to the sheet's porosity. Lindsay was the first to realise that ϕ is the volume fraction available to flow. This does not equal the sheet's porosity, because part of the porosity of the sheet is not available to flow, due to closed pores or differences in permeability (Lindsay 1997).
According to equation 7-1 the flow velocity of a fluid moving through a porous medium depends on the pressure gradient over the medium and the flow resistance met by the fluid. The flow resistance is the ratio of the permeability of the medium to the fluid and the fluid's viscosity. The viscosity is a material property of the fluid affected only by the temperature in the porous medium. The permeability of the medium to a certain fluid is a characteristic of the porous medium.

The permeability is determined by the following factors:
- Void fraction available to flow;
- Tortuosity of the pores.

Experimental evidence obtained in chemical engineering teaches us that the Kozeny Carman equation (equation 7-1) can be rewritten into the Blake-Kozeny equation (Bird et al. 1960), cf. equation 7-2.

$$v = \frac{K\,\partial p_H}{\mu\ \partial z}$$

$$K = \frac{C \quad \phi^3}{r^2\ (1-\phi)^2}$$

equation 7-2

In which *C* and *r* are the only new variables compared to equation 7-1. *C* represents a material-dependent constant, and *r* represents a characteristic pore radius [m].

This means that in practice the permeability is a function of the material constant C and two variables:
- Void fraction available to flow;
- Characteristic pore radius.

This means that it may be important to determine the pores through which most of the water will flow when leaving the web. This depends on two factors:
1. The total void volume located in pores of a certain ratio;
2. The permeability of the pores to water, this is proportional to r^{-2}, cf. equation 7-2.

The pore-size distribution may change due to the significant compaction during wet pressing. Therefore, the pore-size distribution as a function of density is of interest for predicting the dewatering speed of a wet sheet under pressure. The pore-size distribution may change in the following ways:
- The number of pores decreases;
- The average pore length decreases;
- The average pore width decreases;
- A combination of the above.

7.3 Mercury porosimetry

Mercury porosimetry can be used to determine the pore-size distribution of a porous network. It's working principle can be explained in terms of the behaviour of non-wetting liquids in capillaries. Non-wetting liquids are liquids with a wetting angle in excess of 90°. Most non-wetting liquids are non-wetting in combination with a specific solid surface, whereas they are wetting on another type of surface. For example, water is a wetting liquid on a clean glass plate, on which the water will spread as widely as possible (wetting angle = 0°), whereas the water will form droplets (wetting angle

> 90°) on a waxed glass plate.

A non-wetting fluid will maximise the contact with the other fluid particles, while minimising the contact with the solid surface. Within a pore this means, that it will form a convex surface. Under the convex surface, the pressure will equal the sum of pressure exerted by the surroundings and the pressure due to the surface tension, the so-called capillary pressure (Atkins 1990). Therefore, in order to force a non-wetting liquid into a pore, a force counteracting the capillary pressure has to be exerted on it.

The capillary pressure is calculated according:

$$p_c = \frac{2y \cos \theta}{r}$$

equation 7-3

In which p_c represents the capillary pressure, i.e. the pressure caused by surface tension [N/m^2], y is the surface tension [N/m], θ is the wetting angle [degrees], and r is the equivalent circular pore radius [m].

The wider the pore size, the lower the pressure needed to overcome the capillary forces. Therefore, the pore-size distribution can be measured by gradually increasing the pressure on a vessel containing a piece of paper submerged in a non-wetting liquid and measuring the intake of the non-wetting liquid by the paper after each increase of pressure. In this way a cumulative pore volume can be determined as a function of the applied pressure, starting with the volume of the largest pores. The product of the pressure and the pore radius is a constant for the combination of a porous solid and a non-wetting liquid. This means that, rather than the actual pore size, this method measures the force needed to make the non-wetting liquid to flow into the pore. From this force an estimation of the pore size radius is derived, based on the assumption that the pore is cylindrical in shape. Real pores are never exactly cylindrical, therefore the measured pore radius is an equivalent circular pore radius. Nevertheless, this information will provide a good estimate of the effect of the compaction on the characteristic size of the pores available to flow.

The mercury porosimetry measurement yields a cumulative pore volume starting at the widest pores, cf. figure 7-1. From these data a pore-size distribution can be derived by plotting the increase in pore volume with each smaller pore radius that becomes accessible. This figure shows, for each pore radius size, the pore volume accessible through pores with a radius of this size, cf. figure 7-2.

Compression decreases the total pore volume. The question is, how does the pore-size distribution change with a decreasing total pore volume? There are several options.

- Decreasing the length of all pores without changing the pore-size distribution, cf. figure 7-3.
- Closing the large pores without affecting the volume of the other pores, cf. figure 7-4
- Decreasing the width of all pores, causing a shift of the pore-size distribution towards smaller pore sizes, cf. figure 7-5.

Option 1 (figure 7-3) implies that, apart from the decreasing void volume, no changes to the pore-size distribution will occur. This would mean that the parameter C/r^2 is a material constant. The permeability of one type of furnish varies only as a function of the compaction.

Option 2 (figure 7-4) assumes that most of the pore volume is located in a pore of a certain characteristic radius and that this remains the same during wet-pressing. However, water tends to choose the flow path of least flow resistance, i.e. wider pores. So, if the wider pores are closed this may have a significant effect on the permeability of the sheet for a significant part of the water, depending on the amount of water flowing through the wide pores before and after compaction.

Option 3 (figure 7-5) implies that per type of furnish the permeability is a function of the pore volume available to flow and of the way in which the pore-size distribution changes with decreasing pore volume. This implies that per type of furnish the relation between the total pore volume available to flow and the characteristic pore size needs to be determined.

7.4 Experimental

7.4.1 Mercury porosimetry measurements

The pore volume of all sheets was determined using a Carlo-Erbach porosimeter. Mercury was applied as a non-wetting liquid, since it does not wet the fibres and does not change the three-dimensional structure of the paper.

The wetting angle of mercury depends on the nature of the paper sample. The wetting angle has been measured on a large number of samples using X-rays. The values have been reported to vary between 135 and 142 degrees. Surface tension of mercury to air depends on temperature and at 25 ^{o}C is 473 dynes/cm (i.e. 4.73*10^{-5} N/m) (Hodgman 1946).

Surface roughness is known to increase the wetting angle of non-wetting fluids. In view of the relatively high surface roughness of paper fibres the wetting angle was assumed to be 142 degrees.

Substitution of these data in equation 7-3 resulted in the following expression for the pore radius. This equation was used to calculate equivalent pore size radii.

$$r = \frac{0.75}{p} \qquad \textit{equation 7-4}$$

In which r represents the radius of the pore [m], and p represents the absolute pressure applied [N/m^2], which equals the capillary pressure p_c.

This equation is in good agreement with the data used by Kettle et al. (Kettle et al. 1993).

7.4.2 Furnishes

All tests were carried out on samples made of two different types of virgin fibres: thermo-mechanical pulp (TMP) and bleached kraft hard wood (BKHW) pulp. The TMP was produced at the Norske Skog-Parenco newsprint mill and air dried at TNO, the BKHW was obtained as dry bales.

After dispersing the pulps were immediately used to make hand sheets. Hand sheets were made using a sheet former equipped with a 80 mesh sieve. Additionally, machine sheets were made on the pilot machine of PKI[1]. The hand sheets were made of BKHW pulp and TMP. Hand sheets were made of the unrefined pulps. The paper machine sheets were made after slightly refining the BKHW pulp. The freeness of the pulps was determined using the Schopper-Riegler test. The TMP had a freeness of 60-70 SR, the unrefined BKHW had a freeness of 25-30 SR, and the refined BKHW pulp had a freeness of 40 SR (corresponding to 100, 675, and 300 CSF, respectively).

| [1] PKI stands for Papiripari Kutatóintézet, the name of the Hungarian Pulp and Paper Research Institute.

The samples cut from the hand sheets were pressed in a platen press for three minutes between blotter paper to pressures varying between 0.0, 0.1, 0.5, 1.0 and 2.0 MPa, respectively. The machine sheets were pressed in two nip press section of a small pilot paper machine. The pressure applied in these nips was; 0.0 and 0.0 MPa, 0.3 and 0.0 MPa, 0.3 and 0.3 MPa, 0.0 and 1.0 MPa, 0.3 and 1.0 MPa, and 1.0 and 1.0 MPa, respectively. The pilot press was operated at approximately 10 m/min. Additionally a series of TMP sheets was made on a Rapid Köthen sheet former fitted with a 100 mesh sieve, and compressed to completion at pressures varying between 0.1, 0.5, 1.0 and 4.0 MPa to study the effect of formation and to allow for direct comparison with the results in the next chapters.

7.5 Results

Figure 7-6 shows the pore-size distribution as measured on an unpressed TMP hand sheet. This pore-size distribution showed two significant peaks. One occurred at a radius of 3.5 micron and the other at a pore radius of 20 micron. Apparently these pore radii were characteristic for this unpressed TMP hand sheet formed on a hand former equipped with an 100 mesh sieve.

Figure 7-7 shows how this pore size distribution changes due to compression to respectively 0.1, 0.5, 10 and 2.0 MPa, respectively. During the initial compaction to 0.1 MPa the void volume in the sample decreased, but the pore-size distribution remained the same as shown in figure 7-3. Therefore, the factor $C\,r^2$ remained constant. However after this initial compaction the pore-size distribution changed significantly.

The pore size distribution of the samples made of unrefined BKHW pulp changed in a different way than the samples made of the TMP pulp. Figure 7-8 shows that the density increase is mainly caused by the closure wide pores as shown in figure 7-4. In the most compacted state 85% of the volume was located in the pores smaller than 10 micron.

Apparently, the compaction behaviour is different per furnish type. However, both the samples made of TMP and of BKHW hand sheets had a characteristic equivalent pore radius at about 3.5 micron and at about 15 micron.

To determine the effect of forming method we compared the pore-size distribution of unpressed samples made from hand sheets produced on a hand former with samples produced on a Rapid Köthen sheet former, cf. figure 7-9. Both pore-size distributions

show a peak at about 3.5 micron. However, a significant difference in pore-size distribution occurs at the wider pores. Apparently the compaction of the wide pores has already occurred, or the wide pores are formed to a lesser extent during forming on the Rapid Köthen. This may be explained by the finer mesh sieve and the higher vacuum used on the Rapid Köthen. The Rapid Köthen was equipped with the 80 mesh sieve and applied 0.03 MPa vacuum while the hand former was equipped with a 100 mesh sieve and applied a 0.015 MPa vacuum at most.

Figure 7-10 shows that the pore size distribution of the Rapid Köthen formed sheets changes proportionally as explained in figure 7-3 when the sheets are compacted. This is of importance since the formation on a paper machine is probably more like the formation on the Rapid Köthen than like the formation of the hand former.

To check the effect of the fibre properties on the pore size distribution and the compaction of the pore size distributed measured the pore-size distributions of refined BKHW samples formed on the forming section of a low-speed pilot machine before and after compaction by various loads in the first and or second nip, cf. figure 7-11.

The pore volume of the refined samples was significantly lower than the pore volume of the unrefined BKHW samples, cf. figure 7-8. Apart from the total pore volume the pore-size distribution of the unpressed sheets varied only in the size of the characteristic equivalent pore radius. In case of the refined BKHW the equivalent pore radius equalled 2.3 and 15 micron while in case of the unrefined BKHW the equivalent pore radius equalled 3.5 and 15 micron. However the pore size distribution of the refined BKHW changed differently due to compaction than the pore size distribution of the unrefined BKHW, cf. figure 7-8.

Figure 7-12 shows that this difference is not caused by a difference in formation method, because the pore-size distribution of an unpressed and refined BKHW machine-formed sheet had a similar pore-size distribution as an unpressed hand sheet made of the same pulp. Apparently, the differences between figure 7-8 and figure 7-11 were caused by the refining only.

Figure 7-13 allows for a good comparison between the pore size distribution of the unrefined and the refined BKHW both before and after compaction by 1.0 MPa. This clearly shows that:

- The total pore volume is far lower when the fibres are refined;
- The reduction in pore volume results from compaction of the wide pores in case of

the unrefined BKHW, whereas it results from the compaction of the smaller pores in case of the refined BKHW;
- In both cases the compaction causes a shift of the pore-size distribution towards smaller pore sizes.

The first observation indicates that the fibre properties have a strong effect on the pore-size distribution. The second observation indicates that the way in which the pore-size distribution changes with increasing compaction depends strongly on the degree of compaction.

7.6 Discussion

We measured the pore-size distribution of a number of different samples. We saw that formation method, fibre properties and the degree of compaction have a significant effect on the pore-size distribution. The question is, how the pore-size distribution relates to the flow resistance met by the water in the pores.

The interpretation of the data depends on the interpretation of the pore-size distribution. If the paper is regarded as a porous medium with straight pores varying in pore diameter, then the pore-size distribution gives the number of wide pores compared with the number of narrow pores. In that case the characteristic pore radius is the pore radius at which the product of the volume located in the pores and the pore cross-section area is the highest.

For all of the samples that would be a pore radius of about 15 micron.

However, we do not consider this a realistic value. Three-dimensional analysis of paper samples (Auran et al. 1999) showed that the pores in paper have irregular shapes and strongly varying widths. Therefore, we assume that the cumulative pore-size distribution we measured should be regarded as the bottle neck that one has to pass in order to fill part of a pore until the next bottle neck. This means that we expect that most of the pores connecting one side of the paper to another have a pore radius distribution similar to the pore-size distribution we measured. In other words we consider the pore-size distribution measured as an average pore-size distribution of the pores connecting one side of the paper to the other. Therefore, we think that the permeability of the pores only determines the flow velocity through the sheet but not the division of water over the pores.

This has as a consequence that the characteristic pore size as mentioned in equation 7-2 is the pore in which the highest volume fraction is located. This means that the characteristic pore size may change as a function of compaction.

7.7 Conclusions

The aim of this chapter was to determine whether the Blake Kozeny equation, in which the permeability is written as a function of a material constant, a characteristic pore radius, and the void fraction available to flow, would make the calculation of permeability easier. Therefore, we studied the effect of compaction on the pore-size distribution of various samples. The pore-size distributions appeared to be a function of fibre properties, formation, and the degree of compaction.

It appeared that the pore-size distribution of the unpressed samples is determined by the combination of pulp composition and loading of the sample during formation.

We found that, depending on the formation method, the unpressed sample could contain significantly more void space in wide pores. Since the void fraction decreased with increasing dry content after formation, we expect that this is less significant for commercially produced paper. Leaving the effect of the initial compaction out of our consideration, the compaction appeared to cause a more or less proportional change in pore volume, independent of furnish types. This complies with option 1 shown in figure 7-3. Therefore, we expect that a constant value for the characteristic pore radius is a good first estimate to calculate the permeability in this type of sheet.
For the unrefined samples, the pore-size distribution only showed one significant peak. In this case the characteristic pore radius was equal to the pore radius at the peak (r = 3.5 micron). For the refined sheets we found two equally important peaks, so we will assume that the smaller radius determines the flow resistance, and that therefore this radius should be used as the characteristic radius (r = 2.3 micron). We put the measured values of the equivalent pore radius, r, between brackets because we expect them to change as a function of pulp recipe and formation method.

7.8 References

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8 Structural pressure and deformation physics

8.1 Introduction

The mechanical behaviour of the wet web determines the maximum outgoing dryness and the degree of compaction of the wet web. The degree of compaction correlates strongly with various paper properties. Therefore, a thorough insight in the mechanical behaviour of wet web is essential to predict the wet-pressing performance of the combination of a specific furnish with a specific paper machine. Nevertheless, the mechanical behaviour of a wet web during wet pressing is still poorly understood.

The essence of wet-pressing is compaction of the wet web, and removal of water due to the application of a load. The Terzaghi principle states that the reaction force to the application of a load on a porous medium equals the sum of the stress causing the net deformation of the porous medium and the hydraulic pressure related to flow resistance during the removal of water. The first to apply this principle to paper was Campbell (Campbell 1947). Nevertheless, he based his dewatering model on the assumption that during wet-pressing all pressure was counteracted by the flow resistance between the water and the fibre walls. Therefore, he neglected the mechanical behaviour of the web, and based his model completely on the Kozeny equation. A similar approach was followed by Kerekes and McDonald (Kerekes and McDonald 1991).

Nilsson and Larsson acknowledged the importance of the mechanical behaviour of the wet web and incorporated an empirical relation describing the deformation stress as a function of the void fraction, the so-called structural pressure curve (Nilsson and Larsson 1968). This approach was developed some years earlier (Wilder 1960). Riepen and Mulder basically used the same approach, apart from some restrictions that were added to account for the plastic deformation during expansion of the wet web (Mulder and Riepen 1994).

A wet-pressing project was carried out between 1978 and 1984 at the University of Maine, Ontario (UMO), the so-called UMO wet-pressing project. This yielded an equation describing the deformation stress using two elements: an elastic and a plastic part, each as a function of the void fraction (Jewett 1984).

Both the structural pressure curve and the approach used in the UMO wet-pressing project described the mechanical behaviour by an empirical relation without connection with deformation physics. Furthermore, these equations described the lumpsum of the mechanical behaviour of the fibres and the network, and they did not consider the deformation of the fibres separately from the deformation of the network and vice versa. This means that implicitly the assumption was made that fibres are solid and that all water has to overcome the same flow resistance.

However, Carlsson (Carlsson et al. 1977) pointed out that if the outgoing dry content after wet-pressing is higher than the water retention value (WRV), fibre dewatering has to have occurred during wet pressing. According to reports by Busker this was a common situation during commercial papermaking at the time (Busker and Cronin 1982), implying that fibre dewatering is possible within a roll press nip. However, care should be taken with the interpretation of these results since Busker and Cronin most likely used a lower G-force than Carlsson to determine the WRV. Consequently there experiments yielded significantly higher WRVs.

Dynamical pressing tests carried out in the laboratory by Jantunen showed however, that for some furnishes fibre dewatering in a 2.5 millisecond pressure pulse is possible. His experiments showed an increase in dry content from 40% to 44% dry content due to a 2.5 millisecond press impulse on a 80% bleached pine kraft and a 20% bleached birch kraft mixture, cf. figure 8-1 (Jantunen 1985). A time scale of 2.5 milliseconds is of the same order as the time scale in a press nip. Carlsson reported fibre saturation points for bleached kraft pulps between 35% and 40% dry content, implying that a significant degree of fibre dewatering occurred to allow for this increase in dry content (Carlsson et al. 1977).

There are indications that fibre wall collapse is proportional to fibre dewatering (Jang and Seth 1998). When parts of the fibre wall are forced to intimate contact, chemical bonds may be formed (Nissan et al. 1985). The expansion of fibres after wet-pressing is being questioned. Maloney reported that wet-pressing irreversibly closed intra-fibre wall pores, causing hornification of the fibre wall (Maloney et al. 1997). However, the reported results did not directly support this, as they only showed the combined effect of pressing and drying.

Since the role of fibre water had not been studied in relation to the mechanical behaviour of the wet web, we found it necessary to repeat the structural pressure experiments as described in chapter 4 in combination with the test determining the

fibre water content as described in chapter 6. In addition the effect of saturation was taken into account to have an indication of the effect of water on the mechanical behaviour of the wet web.

The models found in literature described the mechanical behaviour by empirical relations obtained under equilibrium conditions (Jewett 1984; Mulder and Riepen 1994; Nilsson and Larsson 1968; Riepen 2000). However, the equilibrium situation will never be reached in the dynamic situation of a commercial press nip. The question is, what is the relevance of these relations in the dynamic situation?

Therefore we studied reports of some dynamical compaction studies. Jantunen (Jantunen 1985) and Vomhoff (Vomhoff 1998) studied the mechanical behaviour of wet webs under dynamic circumstances. Jantunen found that stress relaxation occurred within 100 miliseconds, independent of furnish type. He also reported that the degree of relaxation increased with increasing strain. Vomhoff reported less compaction and more plastic deformation at high strain rates. From these results we concluded that the degree of plasticity of compaction of a wet web is rate-dependent.

Based on Vomhoff's experimental work Lobosco developed a mechanical model in which he described the strain as visco-elastic plastic strain (Lobosco and Kaul 2001a; Lobosco and Kaul 2001b). The model used an empirical relation to describe the plastic strain as a function of the strain rate. Nevertheless, this model significantly improved the current understanding of the mechanical behaviour of wet web. The wet-pressing model presented by Gustafsson incorporated Lobosco's mechanical model (Gustafsson et al. 2001). Gustafsson's model did not distinguish between fibres and network. Therefore, it is not suitable for explicitly modelling fibre dewatering.

Since we expected that fibre dewatering is key to understanding the difference in compaction that may occur between a roll nip and an extended nip press (ENP) or shoe-press nip, we aimed to develop a mechanical model of the wet web distinguishing between the stress caused by the deformation of the individual fibres and the stress caused by the deformation of the network consisting of these fibres.

The aim of this chapter is to develop this model for the mechanical behaviour based on the mechanical tests carried out by Jantunen and Vomhoff and the static experimental tests that are presented in the remaining part of this chapter. Before we present the experiments, methods to express mechanical behaviour in terms of mathematical equations are discussed in the following paragraph.

8.2 Modelling of mechanical properties

The mechanical behaviour of a wet web determines the reaction of a wet web to a pressure pulse. Models exist to describe observations of mechanical behaviour of a material in mathematical terms. Although such models do not necessarily explain the phenomena causing the mechanical behaviour, they are helpful in quantifying observations of mechanical behaviour.

According to deformation theory, stress is the reaction force per area in a material. The following equations describe different types of stress in a wet web. Depending on the type of mechanical behaviour the stress is a function of different parameters. Two main types of mechanical behaviour are distinguished: elastic and viscous deformation. In principle the deformation stress of any type of material can be modelled by these two or a combination of them.

For elastic bodies the deformation stress is linearly related to the strain resulting from the applied load.

$$\sigma = E\varepsilon \qquad \textit{equation 8-1}$$

In which σ represents the deformation stress in the body resulting from the applied load [N/m^2], E the elastic- or Young's-modulus [N/m^2], ε the strain resulting from the load on the structure.

The strain is a measure for the change in dimensions due to the applied load. The generally applicable relation for strain is described as follows (Ludwik 1909).

$$\varepsilon = \int_{h_0}^{h} \frac{1}{h}\,\partial h = \ln\left(\frac{h}{h_0}\right) \qquad \textit{equation 8-2}$$

In which h represents the characteristic dimension of the sample under tension, while h_0 represents the characteristic dimension before applying a load.

For small deformations this equation reduces to Hooke's law, i.e.

$$\varepsilon = \int_{h_0}^{h} \frac{1}{h}\,\partial h \approx \frac{\Delta h}{h_0} \qquad \textit{equation 8-3}$$

From these equations it becomes clear that the deformation stress and strain of an elastic material are supposed to occur immediately upon the application of a load,

and to disappear immediately upon removing the load. Therefore, the symbol for such a material is a spring, cf. figure 8-2 and figure 8-3.

For viscous materials the deformation stress is a function of the rate of strain, i.e. the speed at which the material deforms as a function of the applied load. The strain of a viscous material remains at it's final value when the load is removed. The symbol for such a material is a dash-pot filled with a viscous fluid, cf. figure 8-2 and figure 8-3.

The deformation stress of a viscously behaving material can be calculated using Newton's flow equation.

$$\sigma = \eta \frac{\partial \varepsilon}{\partial t} \qquad \textit{equation 8-4}$$

In which σ represents the deformation stress in the body resulting from the applied load to the structure [N/m^2], η the viscosity in [Ns/m^2], and $\partial\varepsilon / \partial t$ the time derivative of the strain [1/s].

As mentioned before the mechanical behaviour of a material may fit a combination of these basic types of mechanical behaviour. The most elementary combinations are the Maxwell element and the Kelvin-Voigt element.

The mechanical behaviour of a Maxwell element is represented by a spring and a dashpot in series, because it is the sum of the behaviour of a spring and a dashpot, resulting in a partly viscous and partly elastic reaction to the application of a load. This mechanical behaviour is described by the following equations.

The spring and the dashpot are in series thus the stresses are the same for both the elastic and the viscous element of the material:

$$\sigma = \sigma_{el} = \sigma_{v} = \varepsilon_{el} E = \eta \frac{\partial \varepsilon_{v}}{\partial t} \qquad \textit{equation 8-5}$$

In which the subscripts *el* and *v* refer to the *el*astic and the *v*iscous parts of both the stress and the strain.

The strain rate however equals the sum of the individual rates of strain of the elastic and the viscous element of the material, respectively.

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial \varepsilon_{el}}{\partial t} + \frac{\partial \varepsilon_{v}}{\partial t} = \frac{1}{E}\frac{\partial \sigma}{\partial t} + \frac{\sigma}{\eta}$$

equation 8-6

For a constant strain this results in the following equation describing the stress relaxation:

$$\frac{d\sigma}{\sigma} = -\frac{E}{\eta}dt$$

equation 8-7

If $\sigma = \sigma_0$ at $t = 0$, integration results in the following equation describing stress relaxation:

$$\sigma = \sigma_o e^{-\frac{E}{\eta}t} = \sigma_o e^{-\frac{t}{\tau}}$$

equation 8-8

In which τ represents the so-called relaxation time [s], i.e. the time required to relax the stress to the level *1/e* of the initial level σ_0. This equation implies that the stress will disappear if one waits long enough, i.e. $\sigma \rightarrow 0$ if $t \rightarrow \infty$.

The mechanical behaviour of a Kelvin-Voigt element is represented by a spring and a dashpot in parallel, because it is the product of the behaviour of a spring and a dashpot, resulting in a partly viscous and partly elastic reaction to the application of a load. Therefore, during compaction, the mechanical behaviour may be the same as for a dashpot, but during expansion the spring forces the dashpot to return to it's initial position, causing a significantly different behaviour. This is described by the following equation describing the strain.

$$\frac{\partial \varepsilon}{\partial t} = \frac{\sigma}{\eta} - \frac{\varepsilon E}{\eta}$$

equation 8-9

This differential equation yields the following expression to describe the strain during creep, i.e. when the stress is maintained at the constant value σ_0.

$$\varepsilon = \frac{\sigma_0}{E}\left(1 - e^{-\frac{E}{\eta}t}\right) = \frac{\sigma_0}{E}\left(1 - e^{-\frac{t}{\tau}}\right)$$

equation 8-10

Implying that the strain will approach the value σ_0/E, when a constant stress, σ_0, is applied to a Kelvin-Voigt element for a very long period of time, $t \rightarrow \infty$.

8.3 Experimental

All tests were carried out on hand sheets made of two different types of virgin fibres: thermo-mechanical pulp (TMP) and bleached kraft hard wood (BKHW). The TMP was produced at the Norske Skog-Parenco newsprint mill and air dried at TNO, the BKHW was obtained as dry bales. After dispersing, the BKHW was beaten for 1500 rounds at minimum pressure in an Imset differential Mühle für Imitationsmahlung (Imset differential laboratory refiner).

The pulp was divided in two portions. Half of the pulp was used directly to make hand sheets. The other half was first washed over a sieve (mesh 250 micron) before the pulp was used to make hand sheets. The aim of the washing was to remove a significant part of the fines present in the pulp.

Hand sheets were made using a Rapid Köthen sheet former. The sheets were made of the fresh pulps shortly before the tests and stored in a refrigerator until the test. Just before the test circular samples were cut from the hand sheets, using the Zwick Kniehebelpresse in combination with a circular knife of 79.8 mm diameter. The aim of the experiments was to determine the mechanical behaviour of the solid parts of the wet web during loading.

Therefore, we registered the compaction and expansion, the water content, and the water retention value (WRV) after compaction of wet samples. The samples of known ingoing moisture content were pressed to completion. After being pressed to completion the samples were allowed to expand. During compaction and expansion the thickness of the samples was continuously recorded. After expansion the samples were weighed and centrifuged to determine the outgoing moisture content and the WRV.

To determine the effect of moisture on the expansion, samples expanded with and without rewet. Additionally, some samples were pressed several times in a row to test whether the equilibrium moisture content remained constant.

Compaction without rewet was realised by pressing the sample between solid plates, while all excess water was removed by absorption (tissue) before the sample was allowed to expand. The dewatering had to occur in the xy-plane of the sample, this type of dewatering is also referred to as lateral dewatering.
The samples that were tested while rewet could occur were pressed against a porous plate, allowing the water to flow out of the sample across the whole sample surface.

In this type of dewatering the water flowed in the z-direction. Therefore, this type of dewatering is referred to as transversal dewatering. The water was not removed after flowing into the porous plate, it could also flow back into the sample during expansion, causing rewet. However, not all the water removed during compaction flowed back into the sample, this caused a difference in sheet dryness before and after compaction.

8.4 Results

8.4.1 Expansion and rewet

The outgoing dry content correlates strongly to the apparent density of the sheet (Busker 1985). To understand more of this relation we measured the actual wet apparent density after expansion and we also calculated the wet apparent density based on the assumption that the samples remained saturated during compaction. Figure 8-4 shows the calculated wet apparent density plotted against the measured wet apparent density of BKHW samples. The points at which the calculated density equalled the measured density were connected by a line, points on this line represent the samples that remained fully saturated.

Most of the samples lay well below this line, implying that air had flow into the samples. From this we concluded that the samples expanded due to an inner force, causing air or water to flow into the samples. The samples marked z in the legend expanded with rewet. These samples lay close to the line of saturation. Apparently water flew preferably into these samples keeping them saturated during expansion.

In all figures the samples marked by a yellow circle were made of unfractionated pulp. For BKHW the fractionation was not expected to have effect on the apparent density, because of the low initial fines content. Even for TMP the fractionation did not significantly affect the final wet apparent density, cf. figure 8-5.

After compaction the fibre water content was estimated by measuring the WRV. Figure 8-6 shows the WRVs measured on TMP.

The solid line is the line at which the WRV equalled the outgoing moisture ratio, i.e. the points on this line represent samples in which all the water was bound to the fibres. The samples that were expanded without rewet (green symbols) coincide

with the solid line, indicating that after expansion all the water was located within the fibre walls. The WRV of the samples pressed to 4.0 MPa and expanded without rewet lay well below values reported by Carlsson for unpressed TMP, indicating significant fibre dewatering. Fibre dewatering of the samples pressed to 0.5 MPa was insignificant. This confirms the conclusion of chapter 6 that under static conditions fibre dewatering occurs, if the applied pressure is sufficiently high.

The dotted lines indicate the WRV of unpressed TMP as reported by Carlsson (Carlsson et al. 1977). In the case of rewet the WRV of all samples laid within or close to these border lines, implying that fibre rewet occurred. Similar results were obtained on BKHW.

8.4.2 Compaction

To determine the compaction behaviour of purely the network we studied compaction without fibre dewatering and compared this with the compaction behaviour with fibre dewatering.

Figures 8-7 to 8-12 show the results of these experiments. When interpreting these figures the following should be taken into account. The application of a load causes a change in the wet-apparent density, so normally the load would be on the x-axis and the resulting wet-apparent density on the y-axis. Nevertheless we have chosen to plot the results the other way around. We did this because the interpretation of these figures requires comparison to stress-strain diagrams. We expected to help the reader by presenting the results in this way.

Figure 8-7 shows the compaction of wet TMP samples pressed to completion by 0.5 MPa. Figure 8-6 shows that at this load no significant fibre dewatering occurred. The solid lines in this figure show the compaction behaviour of the unpressed samples. The samples compacted proportionally to the applied load. Nevertheless, different stages in the compaction behaviour were registered.

- Initially the compaction increased significantly at low pressure. This was associated with pressing to completion.
- When a sample was pressed to completion, further density increase required a significant pressure increase.
- After the loading had become constant, the density increase continued. When the pressure was relieved, the density initially did not change significantly. However, after the applied load decreased below a certain minimum value, the density rapidly decreased.

Before we draw conclusions, we have to realise that figure 8-7 is not a stress-strain diagram, because most of the time the load does not equal the deformation stress. In most cases a significant part of the applied load was used to overcome flow resistance. To check the significance of this effect we compared the compaction behaviour of saturated samples with the compaction behaviour of unsaturated samples.

The dotted lines in figure 8-7 marked pp show the compaction behaviour of the unsaturated prepressed samples. The initial density of these samples was expected to equal the final density of the unpressed samples, because the prepressed samples started as regular samples before being pressed for a second time. A difference in density existed between a regular sample at the end of a pressure cycle and the density of the same sample at the start of a second pressure cycle. This was caused by expansion during weighing of the samples, because during weighing no pressure was applied to the samples, whereas in the nip a minimum load of 50 N was required to guarantee proper contact with the position sensor.

The first phase of the compaction of the prepressed samples, i.e. pressing to completion, occurred significantly faster than for the unpressed samples. The same results were found in case of compaction of BKHW, cf. figure 8-8. This confirmed the assumption that the first phase is pressing to completion, because the prepressed samples had a significant percentage of air in the void spaces of the sample whereas the unpressed samples were saturated with water. The density and viscosity of air were significantly lower than the density and viscosity of water therefore the compaction to completion occurred significantly faster in case of the prepressed samples.

Furthermore, the prepressed samples appeared to be compacted to a higher density than the unpressed samples. To verify this observation we compacted some samples up to four times. Figure 8-9 shows the registered straining of a representative sample. This figure clearly shows that each time a load was applied to the sample it compacted a bit further than the previous time it was pressed to completion. This means that the wet web relaxed while the load was applied to it. This is in line with observations by Jantunen that the relaxation time, τ, of a wide range of furnishes is below 100 milliseconds.

Extrapolation of the data in figure 8-9 yields the mechanical behaviour of the network alone. From this extrapolation we concluded that the network tended to deform immediately proportionally to the applied load, and that it relaxed if the load was applied during a longer period. This type of behaviour is best described by a Maxwell element.

Figure 8-10 shows how the mechanical behaviour of the wet sample changed when the load was increased to 4.0 MPa. Since the only change was fibre dewatering because of the higher maximum applied load, it seems that the fibres were significantly stiffer than the network. The question is whether the fibres showed viscous or elastic behaviour. The experimental results on WRV, cf. figure 8-6, showed that fibre rewet occurred under static conditions. However the commonly held opinion is that fibre rewet does not occur on the millisecond time scale of a commercial press nip (Jang and Seth 1998; Maloney et al. 1997). Therefore we assumed that the measured fibre rewet occurred due to capillary forces, and that this process is too slow to occur on the millisecond time scale in the nip. This implies that the mechanical behaviour of fibres was regarded as fully viscous. If this assumption proofs to be wrong the model can be easily adjusted by changing the description of the fibres from viscous to Maxwell-element.

8.4.3 Lateral versus transversal dewatering

The experiments were carried out in two different ways:
1. Compaction between solid plates, preventing rewet. We refer to these experiments as lateral dewatering without rewet.
2. Compaction against a porous plate, these experiments are referred to as transversal dewatering. In the latter experiment rewet was not prevented.

In static experiments lateral dewatering is supposed to yield the same results as transversal dewatering, provided that the waiting time is sufficiently long (Ellis 1981; Kruf and Mulder 1994; Mulder and Riepen 1994; Nilsson and Larsson 1968; Paulapuro 2001). Therefore, one method was used to determine the mechanical behaviour without rewet and the other to determine the mechanical behaviour with rewet.

Comparison of figure 8-7 with figure 8-11 and figure 8-8 with figure 8-12 shows some significant differences that may be explained from the differences in the nature of lateral and transversal dewatering.

During transversal dewatering, the rate of strain during compaction was lower than for lateral dewatering. This was explained by the significantly shorter flow path in transversal dewatering than in lateral dewatering, causing a lower flow resistance during transversal dewatering than during lateral dewatering.

The expansion of the transversal dewatered sample started at a higher load than the expansion of the lateral dewatered sample. This may also have been a result of differences between lateral and transversal dewatering, because in transversal dewatering water and air may have flown into the sample at each point of the sample surface that is in contact with the felt or porous plate, while in case of lateral dewatering air could only flow into the sample at the perimeter of the sample. Therefore, the flow path to overcome before any part of the sample becomes saturated with air or water was significantly shorter in the case of transversal dewatering, which resulted in an equally lower flower resistance in case of transversal dewatered samples compared to lateral dewatered samples.

In addition to these expected results we also found that the maximum compaction of the samples during transversal dewatering was about 15% more than during lateral dewatering. This effect was measured both on the TMP and the BKHW samples. According to the present understanding of wet-pressing this should mean that the samples were not pressed to completion. Therefore, we pressed samples for up to 50% longer. Although the sample density increased slightly no significant density increase resulted. This means that the observed difference in maximum compaction is not caused by differences in permeability between transversal and lateral direction, otherwise the increased pressing time should have significantly reduced the difference.

Since the pressure drop is higher during transversal dewatering, a likely explanation of the observed difference in compaction is the dilatation. However, after expansion the transversally dewatered sample had a lower density than the laterally dewatered sample. This indicated that the compaction due to lateral dewatering was more plastic than the compaction due to transversal dewatering, independent of the differences related to the occurrence of rewet. Apparently there is an inherent difference in compaction between lateral and transversal dewatering.

8.5 New theory

The question is how to describe the compaction behaviour of wet webs independent of the furnish characteristics. Additionally, the description of the mechanical behaviour of the wet web has to have a physical meaning in order to provide an alternative to the empirical relations used in the currently applied dewatering models.

We suggest that the viscous effects of flow caused by the dewatering should be considered separately from the viscous effects related to the mechanical behaviour of the fibrous material.

Additionally, we want to consider the deformation of the network separately from the deformation of individual fibres. Therefore we assumed that the total structural pressure in the web is caused by deformation of the network as well as deformation of the fibres. This means that the stress due to the application of a load may be fully located in either the network or the fibres, depending on the characteristics of the wet web and the way in which the load is applied to the web.

Equation 8-11 states that we expect the deformation stress in the network to act in the same direction as the deformation stress in the fibres. In the following we derive the equations describing the structural pressure of the network and the structural pressure of the fibres from the observations made during static and dynamic tests.

$$p_S = p_{S,n} + p_{S,f} \qquad \textit{equation 8-11}$$

In which p_S represents the structural pressure of a wet web, i.e. the total deformation stress [N/m^2], $p_{S,n}$ the structural pressure of the network [N/m^2], and $p_{S,f}$ the structural pressure of the fibres [N/m^2].

In the previous paragraph we concluded that the mechanical behaviour of fibres should be regarded as fully viscous. Therefore, the structural pressure of the fibre is described by the following equation.

$$p_{S,f} = \eta_f \frac{\partial \varepsilon_f}{\partial t} \qquad \textit{equation 8-12}$$

In which $p_{S,f}$ represents the structural pressure of the fibres [N/m^2], η_f the "viscosity" of the deformation of the fibres [N.s/m^2], and $\partial\varepsilon_f / \partial t$ the rate of strain at which the fibres (are forced to) compact [1/s].

The most general definition of strain is applied because the deformation of the fibres may be significant, due to significant fibre dewatering, cf. chapter 6. Additionally, the compressive forces were defined as positive forces. Therefore, the following equation describes the strain of the fibres in a network.

$$\varepsilon_f = \int_{h_{f0}}^{h_f} \frac{1}{h} \partial h = \ln\left(\frac{h_{f0}}{h_f}\right) \qquad \textit{equation 8-13}$$

In which h_f represents a measure of the pore volume inside the outer fibre wall, while h_{f0} represents a measure of the intra-fibre pore volume before applying a load [m].

The average intra-fibre pore volume height, h_f, can be considered a measure for the intra-fibre pore volume, because we are considering the dewatering effect on a macro scale and the web width does not change significantly during wet-pressing. Thus the only variable of the intra-fibre pore volume is the average intra-fibre pore volume height.

In the previous chapter we concluded that the network as a whole behaves like a Maxwell element; the deformation of the network is partly viscous and partly elastic. This results in the following equation describing the relation between the structural pressure of the network and the network strain, in which the network strain is the strain of the wet web without the strain of the fibres:

$$\frac{\partial \varepsilon_n}{\partial t} = \frac{1}{E_n} + \frac{\partial p_{S,n}}{\partial t} + \frac{p_{S,n}}{\eta_n} \qquad \textit{equation 8-14}$$

In which ε_n represents the network strain [m^3/m^3], $p_{S,n}$ the structural pressure of the network [N/m^2], $\partial p_{S,n}/\partial t$ the change in the structural pressure of the network over time [$N/(m^2s)$], E_n the modulus of elasticity of the network [N/m^2], and η_n the viscosity of the network [Ns/m^2].

From the above it follows that the model is based on a description of fibre and network deformation. Therefore we will call it in the following the fibre and network deformation (FND) model.

Figure 8-13 gives a graphical representation of the FND model. The role of the fibres is represented by the dashpot at the left hand side. The dashpot means that the deformation stress in the fibres is proportionally to the rate of strain by which the fibres compact. We assume that deformation of the cellulose strings, forming the fibres, is quite similar to the effect of shearing a twined cable. The deformation

may become plastic directly in the drying section due to chemical bonds, forming between different parts of the fibre wall that are brought in close contact in a relatively dry environment.

The mechanical behaviour of the network formed by the fibres is represented by a Maxwell element, the dashpot and spring in series, at the right side of the figure. For the structural pressure of the network we associate the viscous part of the mechanical behaviour with fibre slippage, which may occur if the part of the applied load, being diverted to shear forces exceeds the yield locus of the web at a contact point between fibres. The elastic part of the structural pressure of the network is associated with compaction and expansion of the porous structure without the fibres in the network changing position.

The dashpot representing the fibres behaviour and the Maxwell element representing the behaviour of the network are in parallel connection. This means that we expect that the wet web as a whole to react like a Maxwell element and a dashpot in parallel, with the network properties determining the Maxwell element, and the fibre properties determining the dashpot. Therefore, when applying a load on the network the stresses divide between the fibres and the network. Within the network the deformation stress is the same in the viscous and the elastic parts. Substitution of this insight in equation 8-11 yields the following equation.

$$P_S = E_n \, \varepsilon_n + P_{S,f} = \eta_n \frac{\partial \, \varepsilon_n}{\partial t} + P_{S,f} \qquad \textit{equation 8-15}$$

The rate of strain of the network is defined as a result of both the elastic and the viscous deformation, cf. equation 8-14. Substitution in equation 8-15 yields the following equation defining the structural pressure as a result of the structural pressure of the fibres, the structural pressure of the network and the loading rate of the network.

$$P_S = P_{S,f} + \frac{\eta_n}{E_n} \frac{\partial p_{S,n}}{\partial t} + P_{S,n} \qquad \textit{equation 8-16}$$

In which p_S represents the total structural pressure in the web [N/m^2], $p_{S,f}$ the structural pressure of the fibres [N/m^2], $p_{S,n}$ the structural pressure of the network [N/m^2], E_n the modulus of elasticity of the network [N/m^2], and η_n the viscosity of the network [Ns/m^2].

This equation perfectly explains the observation made by Vomhoff that a rapidly applied load compacted a wet web to a lesser extent than a slowly applied load.

The above mentioned equations constitute the FND model, describing the mechanical behaviour of the wet web. To determine the validity of this model we tried how it describes the behaviour of the wet web as a function of the applied time scale. For this aim we used the following experiment of thought:

Figure 8-14 shows the structural pressure resulting from an imaginary pressure pulse on a wet web. The time scale of this pressure pulse is variable.

Figure 8-15 visualises the three different reactions that are predicted by the FND model. The indicated time scales are estimates; the exact values can only be determined when the characteristic modulus of elasticity and the viscosity of both the network and the fibres are known.

The picture on the left of this figure shows the effect of a very fast pressure pulse, much faster than will occur in current paper machines. In this case the equation predicts that viscous forces prevent any significant deformation, implying an inherent limit to the speed at which a web can be dewatered due to wet-pressing.

The picture on the right of this figure shows the effect of a very slow pressure pulse. In this case the deformation is expected to be fully elastic. This is less realistic since, especially with a high ingoing water content, fibre slippage will always occur and therefore part of the network deformation will always be plastic. However, wet-pressing is such a dynamic process that the deviation in this limiting case seems less important.

The central picture shows the situation as it occurs on time scales between these two limiting cases. This is by definition the time scale occurring on commercial press nips, because that is the situation for which the FND model was derived.

The central picture shows that with increasing structural pressure the strain will increase more than linearly, while with decreasing pressure part of the strain will appear plastic. The faster the straining, the higher the percentage of plastic strain.

8.6 Conclusions

The wet-pressing performance was determined by measuring compaction and dewatering rates. The structural pressure appeared to play an important role both

in determining the flow rate from the web and in determining the final degree of compaction after wet-pressing. Therefore, proper understanding of the structural pressure seems essential if we are to optimise the wet-pressing performance.

Current equations for the structural pressure describe the compaction behaviour of the wet web, not the expansion. The role of fibres and network is lumped together. We have presented a new model, describing the mechanical behaviour of the wet web during both the compaction and the expansion. In this model the roles of fibres and network are considered separately. The network and fibres are expected to work in parallel. The contributions of the network and the fibres to the structural pressure of the wet web are described in terms of viscosity and E-modulus. These descriptions are linked to phenomena occurring during wet-pressing. Therefore the model was called the fibre and network deformation (FND) model.

Fibre rewet was measured on a long time scale. Nevertheless, no such effect has been measured on the short time scales occurring in commercial press nips. Therefore, we expect the fibres to deform as a viscous medium, whereas the network is expected to deform like a Maxwell element. It will require dynamic tests to determine the viscosity of the network and the viscosity of the fibres.

The new model for web deformation has not yet been validated. Nevertheless, it explains the following observations made in dynamic press simulations(Vomhoff 1998):

- The maximum deformation is lower at high strain rates than at low strain rates.
- The degree of plastic deformation is higher at high strain rates.

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9 Effect of press nip geometry on density

9.1 Introduction

The selling argument for a shoe nip press or an extended nip press (ENP) is the lower density ratio that may be obtained compared to roll nip presses pressing to the same dryness. Reports show that in particular for paper produced from chemical pulps, the density may be significantly lower after wet-pressing to the same outgoing dry content than before installing a shoe nip press (Busker 1986; Lange 1996).

Conventional dewatering theory offers no explanation. We think that this is because of the following characteristics of conventional dewatering theory:

- Inter-fibre and intra-fibre dewatering are lumped together (Jewett 1984; Kerekes and McDonald 1991; McDonald and Kerekes 1991; Mulder and Riepen 1994; Nilsson and Larsson 1968; Riepen 2000).
- Empirical models for structural pressure without relation with deformation physics. The older models use essentially elastic descriptions for the mechanical behaviour of the wet web. The model developed by the University of Maine dewatering project (Jewett 1984) distinguishes between elastic and plastic deformation. Riepen used a special parameter to correct for non-elastic behaviour (Mulder and Riepen 1994). The disadvantage of this parameter is that it has to be experimentally determined for the exact machine-furnish combination. Gustafsson (Gustafsson et al. 2001) incorporated the mechanical model developed by Lobosco and Kaul (Lobosco and Kaul 2001). Their model described the wet web as a visco-elastic plastic material. It was capable of predicting a difference in compaction between a web of a chemical pulp and a web made of a mechanical pulp. Nevertheless, it remained a black-box description of the mechanical behaviour of a wet web.

There is an 'unofficial' explanation for the difference in density due to a difference in press type. This theory is unofficial in the sense that it has not been published in a peer reviewed article. We call it the 'entanglement theory', because according to this theory the difference is explained by a higher degree of entanglement of fibres during wet-pressing in roll nip presses than during wet-pressing in a press section including an ENP.

This theory is graphically represented in figure 9-1 and figure 9-2.

Basically, the entanglement theory states that the higher density after compaction in a roll nip press section is explained by the higher degree of fibre entanglement after compaction in a roll press nip than after compation in a shoe press nip. This higher degree of entanglement is expected to inhibit expansion, and consequently, resulting in a lower bulk.

The occurrence of this higher degree of fibre entanglement is explained as follows. If the web is compacted to the same dry content, on average the contact between the fibres should be the same in a roll and in a shoe nip press, because the outgoing dry content is reached at maximum compaction. At this point the web is fully saturated. This means that, independent of the type of nip, the web has to be compacted to the same degree to reach the same outgoing dryness. However, the roll nip is expected to cause a gradient in the density, while the shoe nip press is expected to compact the web evenly across it's thickness. Therefore, entanglement may occur in the roll nip press whereas it should not occur in the shoe nip press.

Based on the entanglement theory a difference in bulk should be expected when changing a roll nip for a shoe press when producing heavy board made of recycled fibres. Since this board is really heavy, a roll nip press will cause a high density gradient, while a shoe nip press will compact the web evenly. Little effect should be expected on tissue paper made of virgin chemically pulped fibres, because this is too thin to allow for a gradient in the z-direction. However, the opposite can be observed on commercial machines around the world. This untangles the entanglement theory.

Therefore, a different approach is needed to gain new insight.

Vomhoff and Lobosco (Lobosco 2000; Vomhoff 1998) presented experimental work obtained on a hydraulic press capable of reproducing the press pulse applied in a commercial nip. They observed that compaction was more plastic if the deformation occurred at high speed. Furthermore, they also observed that it was more significant when compacting samples made of fibres with a high fibre saturation point.

Therefore we assumed that the reported differences in density between a wet web dewatered in a roll nip and one dewatered in a shoe nip (Busker 1986; Lange 1996) were caused by differences in fibre dewatering. This also explains why this difference was reported for furnishes made of chemically pulped fibres and not for mechanically pulped fibres, since the water content of chemically pulped fibres is significantly

higher (Carlsson et al. 1977) and the force that the fibre walls will resist before water is pressed from the walls is significantly lower (Scallan and Tigerström 1992).

Further reasoning brought us the conclusion that the difference in densification between a roll press and a shoe press is linked to the intra-fibre dewatering. To verify this theory, the ratio of inter-fibre dewatering and intra-fibre dewatering should be calculated explicitly. Therefore the aim of this chapter is to use the insights obtained in the previous chapters to develop a new model. This model should allow for the simultaneous calculation of the compaction and the dewatering in such a way that it helps to analyse why a difference in bulk may exist between two identical furnishes pressed to the same outgoing dry content by either a roll nip press or an ENP.

9.2 Model derivation

The exact three-dimensional geometry of a wet web is very difficult to measure. In addition the geometry changes rapidly and dramatically during wet-pressing. Therefore, we have chosen a macroscopic approach to describe the compaction during wet-pressing. Chapter 3 explains which assumptions are implicitly made when describing the compaction of a wet web on macro scale.

In the following we derive the equations, describing the force balance, the deformation stress and the flow resistance.

9.2.1 Force balance

The Terzaghi principle is a force balance on the macro scale. It states that the load applied to the wet web during wet-pressing results in two reaction forces in the wet web: the hydraulic pressure in the water and the deformation stress in the solid phase. The hydraulic pressure is caused by the force necessary for the water to overcome flow resistance. The deformation stress is the reaction force in the material resulting from the deformation. In paper physics it is called the structural pressure.

$$\sigma_T = p_S + p_H \qquad \textit{equation 9-1}$$

In which σ_T represents the total load applied to the surface area [N/m^2], p_S the structural pressure resulting from the deformation of the solid parts of the web [N/m^2], and p_H the hydraulic pressure in the web [N/m^2].

Unlike the soil particles from which Terzaghi derived his equation, fibres are not solid particles. Therefore, we have to further specify the phases in the porous network. The different phases that can be distinguished in the wet web are:

- Solid structure of the fibre
- Intra-fibre water, i.e. the water inside the fibres
- Solid network structure formed by fibres, fillers and fines
- Inter-fibre water, i.e. the water between the fibres

We distinguish between fibres and the network, because fibres and network may be deformed to a different extent, depending on the pressure pulse being applied. The wet web may not be saturated and may thus include both water and air, cf. chapter 8. This means that the structural pressure is the sum of the structural pressures of both the network and the fibres, as shown in the previous chapter.

9.2.2 Equation of flow

Figure 9-3 shows the cross-section of a dry, commercially produced sheet. During wet pressing the void volume is at least twice the void volume shown. Nevertheless, this picture clearly shows, that the flow of water and air through wet paper is essentially the flow of fluids through a bundle of curved tubes of irregular cross section. Therefore, it seems reasonable to characterise the flow through the intra-fibre and inter-fibre pores in terms of laminar flow through tubes, cf. paragraph 3.4.3 for the determination of the flow type.

Laminar flow through straight tubes of constant diameter can be described using the Hagen-Poisseuille law. In the following the Kozeny-Carman equation for flow through a porous medium will be derived from the Hagen-Poisseuille law. This exercise shows the meaning of the different parameters in the Kozeny-Carman equation for the specific situation of a wet paper web. Using this insight we will derive a set of equations, describing separately the flow from and into the intra-fibre pore spaces (the pore spaces within the fibres), and the flow from and into the inter-fibre pore spaces (the pore spaces between the fibres).

According to the Hagen-Poisseuille law for laminar flow in cylindrical tubes of diameter D, the average flow velocity is written as follows.

$$\langle v \rangle = -\frac{R^2 \, \Delta p}{8\mu \, L} \qquad \textit{equation 9-2}$$

In which <v> represents the average flow velocity in a tube [m/s], due to a pressure difference Δp [N/m^2] along the length of the tube L [m], R represents the radius of the tube [m], and μ represents the viscosity of the fluid flowing through the tube [kg/m s].

For a wet web the pressure difference becomes the hydraulic pressure difference across the inter-fibre pores, i.e. the voids between the fibres. Furthermore, the pores are not straight tubes. Therefore, the radius R has to be replaced with the hydraulic radius R_H.

$$v_n = -\frac{R_H^2}{8\mu}\frac{\partial p_{H,n}}{\partial z} \qquad \textit{equation 9-3}$$

In which v_n represents the actual flow velocity in the inter-fibre pores [m/s], R_H the hydraulic radius of the pore [m], μ the fluid's viscosity [Pa s], and $\partial p_{H,n}/\partial z$ the hydraulic pressure gradient in the inter-fibre pores across the web thickness [N/m^3].

The hydraulic diameter is defined as the cross-section available to flow and the wetted perimeter. If the porous medium consists of spherical solid particles, the hydraulic radius can be written as shown in equation 9-3.

$$R_H = \frac{6}{D_p}\frac{\phi}{1-\phi} \qquad \textit{equation 9-4}$$

In which R_H represents the hydraulic radius [m], D_p the characteristic diameter of the spherical particles [m], and ϕ the porosity of the packed bed [m^3/m^3].

If the particles are not spherical, equation 9-4 changes into the so-called Kozeny-Carman equation.

$$v_n = -\frac{K_n}{\mu}\frac{\partial p_{H,n}}{\partial z} \qquad \textit{equation 9-5}$$

In which v_n represents the superficial flow velocity in the inter-fibre pores [m/s], K_n the network's permeability to the water [m^2], μ the viscosity of the water [Pa s], and $\partial p_{H,n}/\partial z$ is the hydraulic pressure gradient in the inter-fibre pores across the web thickness [N/m^3]. If the web is not saturated the permeability is the permeability of the network to the water/air mixture, and the viscosity is the viscosity of the water/air mixture.

$$K_n = \frac{1}{\tau S_{n0}^2} \quad \frac{\phi^3}{(1 - \phi_n)^2}$$

equation 9-6

In which K_n represents the network's permeability to the water or the water/air mixture [m^2], τ is a constant to correct for the tortuosity of the pores [m/m], S_{n0} is the surface area of the inter-fibre pores per unit volume of solid material [1/m], and ϕ_n is the volume fraction available to flow formed by the inter-fibre pores [m^3/m^3].

According to the Blake-Kozeny equation the permeability equation can be reduced to a function of the volume fraction available to flow and a characteristic dimension of the inter-fibre pores. In chapter 7 we studied some furnishes and we reported that the expected value for the pore radius was furnish-dependent, although it appeared to be independent of the degree of compaction. As a result, the pore radius appears suitable for use as a characteristic pore dimension. This results in the following equation for the permeability.

$$K_n = - \frac{C_n}{r_n^2} \quad \frac{\phi_n^3}{(1 - \phi_n)^2}$$

equation 9-7

In which K_n represents the network's permeability to the water and air mixture [m^2], C_n a material constant, r_n the characteristic pore radius [m], and ϕ_n the volume fraction available to flow, formed by the inter-fibre pores [m^3/m^3].

$$\phi_n = \frac{h_n}{h_n + h_{S0}}$$

equation 9-8

In which ϕ_n is the volume fraction available to flow formed by the inter-fibre pores [m^3/m^3], and h_n and h_{s0} represent the void volume between the fibres per area and the volume of fibrous solid per area [m].

For a porous medium consisting of solid particles, ϕ_n equals the porosity. However, paper fibres are not solid. This may explain why several authors have failed in their attempts to relate the permeability to the overall porosity of the wet web. Lindsay (Lindsay 1997) realised; that an effective void fraction had to be used and was thus able to relate experimental data on dewatering to the Kozeny-Carman equation.

This means that, contrary to common belief; the definition of ϕ_n, i.e. the volume fraction available to flow formed by the inter-fibre pores, cf. equation 9-8, deliberately excludes the pore volume inside the fibres. In formula form this may be written as follows.

$$e_n = \frac{h_n}{h_n + h_f + h_{s0}} \quad \wedge \quad \phi_n \neq e_n \qquad \textit{equation 9-9}$$

In which e_n represents the volume fraction located between the fibres, ϕ_n the volume fraction available to flow formed by the inter-fibre pores [m^3/m^3], and h_n, h_f and h_{s0} are the void volume between the fibres, the void volume within the fibres and the volume of fibrous solid per area, respectively [m].

There is a significant difference in scale between the size of the inter-fibre pore radii and the intra-fibre pore radii (Maloney et al. 1997). Therefore, flow into and out of the sheet is expected to occur as flow through the inter-fibre pore spaces. The driving force for flow is the pressure gradient across the thickness of the sheet. The fibres are considered to act like water sources or sinks. Water may enter or leave the fibres, but flow through the fibres is assumed to be insignificant for the distribution of the water. Therefore, we derived the following equations to describe the flow from the intra-fibre pore space to the inter-fibre pore space and vice versa.

$$v_f = - \frac{K_f}{\mu} \frac{\Delta p_{H,f}}{R_f} \qquad \textit{equation 9-10}$$

In which v_f represents the superficial flow velocity out of the intra-fibre pores [m/s], K_f the permeability of the intra-fibre pore space [m^2], μ the fluid's viscosity [N s/m^2], and $\Delta p_{H,f}/R_f$ the difference in hydraulic pressure across the fibre wall [N/m^3].

More precisely, $\Delta p_{H,f}/R_f$ represents the driving force for the flow from or into the intra-fibre pore space, i.e. R_f may be less than the fibre-wall thickness, as is the case if most of the water comes from the fibre wall rather than from the lumen. Nevertheless, fibre wall thickness seems to be a suitable initial estimate for R_f.

The permeability of the fibre walls is described by:

$$K_f = \frac{C_f}{r_f^2} \frac{\phi_f^3}{(1 - \phi_f)^2} \qquad \textit{equation 9-11}$$

In which K_f represents the permeability of the intra-fibre pore space [m^2], C_f a dimensionless material constant, r_f the characteristic pore radius of the intra-fibre pores [m], and ϕ_f the volume fraction available to flow, formed by the intra-fibre pores [m^3/m^3].

$$\phi_f = \frac{h_f}{h_f + h_{S0}} \qquad \textit{equation 9-12}$$

In which ϕ_f represents the volume fraction available to the flow formed by the intra-fibre pores [m^3/m^3], and h_f and h_{s0} represent the void volume within the fibres per area of sheet and the volume of fibrous solid per area, respectively [m].

Similar to the definition of the volume fraction available to flow in the inter-fibre pore spaces, the definition of the volume fraction available to flow in the intra-fibre pore spaces, ϕ_f deliberately excludes the volume located within the inter-fibre pores, since including it would increase the void fraction available to flow inside the fibres by decreasing the void volume between the fibres, which does not make sense.

9.2.3 Structural pressure

The deformation of a wet web is the result of deformation of individual fibres, deformation of the network formed by the fibres, or a combination of the two. This means that the structural pressure of the wet web is the sum of the structural pressure of the fibres and the structural pressure of the network. Based on these considerations we derived an equation for the structural pressure in the previous chapter.

$$p_S = p_{S,f} + \frac{\eta_n}{E_n}\,\frac{\partial p_{S,n}}{\partial t} + p_{S,n} \qquad \textit{equation 9-13}$$

In which p_S represents the total structural pressure in the web [N/m^2], $p_{S,f}$ the structural pressure of the fibres [N/m^2], $p_{S,n}$ the structural pressure of the network [N/m^2], E_n the modulus of elasticity of the network [N/m^2], and η_n the viscosity of the network [Ns/m^2].

This equation explains perfectly the observation made by Vomhoff that a rapidly applied load compacted a wet web to a lesser extent than a slowly applied force.

9.3 Analysis

We saw that the strain of a wet web consists of the strain of the fibres and the strain of the network. The strain of the network is partly reversible and partly irreversible, whereas the strain of the fibre is fully irreversible on the time scale of the nip residence time. In this chapter we will study how this affects the final compaction in a roll nip press and an shoe nip press.

According to the current general opinion an ENP favours fibre dewatering, because an ENP has a longer nip residence time. This is a relevant aspect, because fibre dewatering is proportional to the fibre wall permeability, Kf. Since the dimensions of the intra-fibre pores are significantly smaller than the dimensions of the inter-fibre pores, the permeability of the intra-fibre pores is expected to be an order of magnitude 10 or more less than the permeability of the inter-fibre pores, Kn. This means that intra-fibre dewatering is expected to be slower than inter-fibre dewatering, as a result of which a longer nip residence time favours fibre dewatering.

The question is how relevant the dewatering speed is. The distance to be travelled by the water in order to leave the fibre is probably a factor 5-10 shorter than the distance the water has to travel to leave the web. Furthermore, fibre dewatering is proportional to the fibre wall permeability, but it is determined by the driving force for flow. If driving force for fibre dewatering is the same in a roll nip press as in an ENP, an ENP is more likely to yield a high degree of fibre dewatering because of the before mentioned permeability difference between the intra-fibre and the inter-fibre pore space. However, if the driving force for flow in an ENP is significantly lower than the driving force for flow in a roll nip press, this difference in driving force may be more important than the difference in permeability. In the latter case it may well be possible that a higher degree of fibre dewatering occurs in a roll nip press. Therefore, we will take a closer look at the driving force for fibre dewatering as defined by our model.

Equation 9-10 describing the flow into and out of the intra-fibre pore space describes the pressure drop in the hydraulic pressure across the fibre wall, $\Delta p_{H,f}$, as the driving force to flow.

The drop in hydraulic pressure is the difference between the hydraulic pressure in the intra-fibre pore space, $p_{H,f}$ and the hydraulic pressure between the fibres in the inter-fibre pore space, $p_{H,n}$. The hydraulic pressure in the intra-fibre pore space, $p_{H,f}$, is equal to the difference between the applied load and the structural pressure of the fibre, $p_{S,n}$. This is described by the following equation.

$$p_{H,f} = \sigma_T - p_{S,f}$$ *equation 9-14*

In which $p_{H,f}$ represents the hydraulic pressure in the intra-fibre pores [N/m²], $p_{S,f}$ the structural pressure of the fibres [N/m²], and σ_T the applied load to the wet web [N/m²].

The hydraulic pressure in the inter-fibre pore space, $p_{H,n}$, is equal to the difference between the applied load and the structural pressure of the web, p_S. Substitution of equation 9-13 results in the following equation, describing the hydraulic pressure in the network.

$$p_{H,n} = \sigma_T - p_S$$

$$= \sigma_T - \frac{\eta_n}{E_n} \frac{\partial p_{S,n}}{\partial t} - p_{S,n} - p_{S,f}$$ *equation 9-15*

In which $p_{H,n}$ represents the structural pressure in the network, σ_T the applied load to the wet web [N/m²], p_S the structural pressure of the web (both fibres and network) [N/m²], $p_{S,n}$ the structural pressure of the network [N/m²], $\partial p_{S,n} / \partial t$ the change in structural pressure of the network over time [N/(m² s)], $p_{S,f}$ the structural pressure of the fibres [N/m²], E_n the modulus of elasticity of the network [N/m²], and η_n the viscosity of the network [Ns/m²].

This results in the following equation, describing the pressure difference across the fibre wall.

$$\Delta p_{H,f} = p_{H,f} - p_{h,n}$$

$$= \frac{\eta_n}{E_n} \frac{\partial p_{S,n}}{\partial t} + p_{S,n}$$ *equation 9-16*

In which $\Delta p_{H,f}$ represents the pressure difference across the fibre wall [N/m²].

This means that the driving force for fibre dewatering is the structural pressure of the network and the change in the structural network pressure over time. This can be shown by substitution of equation 9-16 in the equation describing fibre dewatering:

$$v_f = - \frac{K_f}{\mu R_f} \left(\frac{\eta_n}{E_n} \frac{\partial p_{S,n}}{\partial t} + p_{S,n} \right)$$ *equation 9-17*

In which v_f represents the superficial flow velocity out of the intra-fibre pores [m/s], K_f the permeability of the intra-fibre pore space [m²], μ the fluid's viscosity [N s/m²], R_f the thickness of the fibre wall [m], $p_{S,n}$ the structural pressure of the network [N/m²], $\partial p_{S,n} / \partial t$ the change in structural pressure of the network over time [N/(m² s)], $p_{S,f}$ the structural pressure of the fibres [N/m²], E_n the modulus of elasticity of the network [N/m²], and η_n the viscosity of the network [N s/m²].

In chapter 8 we found that the network should be modelled as a Maxwell element because of the relaxation of the network stress. Stress relaxation means that the structural pressure of the network decreases over time while the strain remains constant. In this model the decrease is an exponential function of the time, $p_{S,n} \sim e^{(-t/\tau)}$, in which τ represents the stress relaxation time, cf. chapter 8. Jantunen reports that the stress relaxation time is shorter than 100 milliseconds, but significantly longer than 10 milliseconds, 10 ms << τ < 100 ms (Jantunen 1985). This indicates that stress relaxation is insignificant given the nip residence times of commercially operated nips.

Therefore equation 9-17 states that a rapid increase in structural pressure of the network and a high value for the network's structural pressure, i.e. high deformation of the network, favours fibre dewatering. Furthermore the network deformation is determined by the applied load and the compressibility of the furnish. If the dewatering rate is too slow for the nip residence time, the flow resistance counteracts the applied force, and the furnish seems incompressible. On the other hand, if the web is not saturated, or if the flow resistance is very low, the hydraulic pressure in the web will be low and the compressibility will be proportional to the compressibility of the network.

The compressibility of the network depends largely on the fibre properties. For very stiff fibres, e.g. a high percentage mechanical fibres, the compressiblity of the furnish may be low, whereas for chemically pulped fibres the network's compressibility may be high.

Similar reasoning results in the conclusion that the time derivative of the network's structural pressure can only be high if the pressure pulse is short and the compressibility is high. Figure 9-4 shows a schematic representation of the network's structural pressure as a result of the applied load and the compressibility of the network.

As described above, our model predicts that a roll press nip favours fibre dewatering, whereas an ENP favours dewatering of the inter-fibre pores. The same model describes

the mechanical behaviour of the fibre as a viscous element, implying an irreversible deformation of the fibre. Thus more fibre dewatering means more plastic deformation. The mechanical behaviour of the network is described as a Maxwell element, i.e. partly plastic and partly elastic, depending on the speed of compaction. This means that the speed of compaction has a double effect on the plastic deformation. A high network deformation rate increases fibre dewatering and increases the plastic component of the network deformation. This means that according to our model an ENP will yield a lower web density than a roll press nip if the total degree of dewatering is equal in both nips, because a roll press nip dewaters the fibres more, whereas an ENP favours network dewatering.

This means that the model presented in this chapter offers an explanation of the difference in density between paper produced using a roll nip press and paper produced using an ENP. This model agrees with observations of the compaction and expansion behaviour of wet webs.

9.4 Conclusions

Compaction behaviour of wet furnishes has been described in detail (Busker 1986; Jantunen 1985; Lange 1996; Lobosco and Kaul 2001; Vomhoff 1998). The current dewatering theories cannot explain the experimentally determined relation between the rate of strain and the degree of plastic deformation that may occur for certain furnishes.

The effect of straining rate appeared to be stronger for furnishes made of fibres with a high water content. This is an indication that fibre dewatering may be key to understand this phenomenon. Therefore, we developed a dewatering model that explicitly calculates fibre dewatering.

Our dewatering model distinguishes between the void fraction available to flow in the inter-fibre pore space and the void fraction available to flow in the intra-fibre pore space. These void fractions are limited by the porosity but cannot be calculated from it. Due to this differentiation between intra-fibre and inter-fibre void fraction, the Kozeny Carman equation for flow applies to paper.

To estimate the hydraulic pressure in the inter-fibre and intra-fibre pore spaces, the stresses in the paper due to the deformation are necessary. For hydraulic pressure

inside the fibres, $p_{H,f}$, only the deformation of the fibre is relevant. The deformation of the fibres can be estimated independently of the deformation of the network. The hydraulic pressure in the inter-fibre pores is determined by the total applied load minus the part of the load used to deform the wet web. The sum of the deformation stress of the fibres and the deformation stress of the network is expected to equal the deformation stress of the wet web.

Based on a description of the phenomena that are expected to occur during the deformation of the wet web, mechanical models were derived, describing the structural pressure of the fibres and the network.

This model yields the conclusion that the driving force to fibre dewatering is the sum of the network's structural pressure and the time derivative of the network's structural pressure, in which the network's structural pressure is equal to the total applied pressure minus the structural pressure of the fibres.

From the above we may conclude that fibre dewatering is more likely to occur in a roll nip press in which a high maximum pressure is more rapidly applied than in an ENP in which the same press impulse is applied over a relatively long time (lowering both the maximum pressure and the time derivative of the pressure). Furthermore, according to the model a high deformation rate of the network increases fibre dewatering, which is fully plastic, and it increases the plastic part of the network deformation. Therefore, according to the presented model an ENP is more likely to yield a low density sheet than a roll nip press. This means that the presented model is the first model capable of explaining the observations on strain rate-dependent deformation behaviour.

9.5 Future work

In the previous paragraph we concluded that the model in this chapter is the first to provide an explanation to the strain rate-dependent deformation as reported in literature in particular in the case of highly swollen fibres.

However, this model has not been validated yet. The most direct way to test it is to reproduce the difference in bulk on one type of furnish as a funtion of the nip type alone, and to measure whether the fibre water content differs significantly with the type of press.

If this test shows no significant difference in fibre water content or a higher fibre water content in case of the roll nip press, whereas the sheet density is higher in case of the roll press nip the model is proven falls. If this test confirms that the lower density of the wet web compressd in an ENP correlates with a higher fibre water content as predicted by the model, it may be worthwhile to develop a numerical version of the model. If such a version becomes available, the model may be combined with work by Riepen and Bezanovitch on felt dewatering, and with the work presented by Veenstra (Veenstra 2001) on the relation between mechanical behaviour of the web and the press impulse, to determine the effect of changes in the press nip, the felt characteristics, or the furnish composition on wet-pressing performance.

The model may also provide an indication of the sensitivity of a furnish to felt marking, although care should be taken when using the model for this purpose, since this would be a micro-scale application of a macro-scale model.

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